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CHANGES IN CROSS-SECTIONAL AREA OF GATEROADS IN LONGWALLS WITH ROOF CAVING, VENTILATED WITH "U" AND "Y" SYSTEMS

ZMIANY POLA PRZEKROJU POPRZECZNEGO CHODNIKÓW PRZYŚCIANOWYCH ŚCIAN ZAWAŁOWYCH PRZEWIETRZANYCH SPOSOBAMI NA "U" ORAZ NA "Y"

Content: In the paper results of measurements of underground gateroad deformations are presented. The measurements were conducted in seven collieries in the Upper Silesian Coal Basin. Altogether 28 gateroads were analysed:12 longwalls with „Y" and 4 longwalls with „U" ventilation system. Based on results of measurements, changes in cross-sectional area of gateroads were calculated and then referred to their original dimensions (when they were developed). Values of cross-sectional area of gateroads in front of and behind the longwall face are presented. Differences in deformation of gateroads in longwalls with the "U" ventilation system, surrounded by unmined coal, and/or goaf on one side were determined. Changes in cross-sectional area of reused gateroads, and newly driven ones (with a coal pillar separating the goaf from the working), were estimated. For gateroads of the longwalls with "Y" ventilation system their deformations at a distance of 200 metres behind the longwall face was determined. For selected gateroads their convergence was calculated with numerical modeling and a method developed at GIG. Calculations were made with Phase2 software based on the finite element method (FEM). Accuracy of forecasted gateroad deformations were assessed through comparing them with the results of underground measurements.

Keywords: underground mining, gateroads, convergence, numerical modeling

Treść: W Polsce w roku 2012 czynnych było 31 kopalń, a wydobycie węgla kamiennego wyniosło 79,2 mln ton. W 21 kopalniach prowadzono eksploatację w pokładach metanowych, podczas której stwierdzono wydzielanie się metanu do wyrobisk górniczych. Z pokładów metanowych wydobyto łącznie 59,4 mln ton, co stanowi 75% całego wydobycia w roku 2012 (Krause & Sebastian, 2013). Dla zapewnienia bezpiecznej eksploatacji w pokładach metanowych niezwykle istotnym jest zachowanie odpowiednich gabarytów chodników przyścianowych. W polskich kopalniach węgla kamiennego dominują dwa sposoby przewietrzania ścian na „U" z odprowadzaniem powietrza zużytego po caliźnie węglowej oraz na „Y", kiedy to powietrze zużyte odprowadzane jest wzdłuż zrobów za frontem ściany. W przypadku sposobu przewietrzania na „U" (szacuje się że tym sposobem przewietrzanych jest około 75% wszystkich ścian), jednym z kluczowych czynników wpływających na bezpieczeństwo eksploatacji, jest zachowanie odpo-

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wiedniego pola przekroju poprzecznego chodnika wentylacyjnego. Stosując sposób przewietrzania na „Y“, znacznie korzystniejszy z uwagi na zagrożenie metanowe, niezwykle istotne z kolei jest utrzymanie zadawalających gabarytów jednego z chodników za frontem eksploatacji. W artykule przedstawiono wyniki pomiarów deformacji chodników przyścianowych, przeprowadzonych w siedmiu kopalniach węgla kamiennego, które znajdują się w Górnośląskim Zagłębiu Węglowym. Pomiary deformacji przeprowadzono w 12 ścianach przewietrzanych sposobem na „Y“ oraz w 4 ścianach przewietrzanych sposobem na „U“. Łącznie przebadano 28 chodników. W punkcie 2 publikacji przedstawiono podstawowe informacje dotyczące badanych chodników, takie jak: głębokość zalegania, nachylenie pokładu węgla, wytrzymałość na ściskanie skał stropowych, spągowych oraz węgla, wysokość, długość oraz postęp dobowy ściany, jak również otoczenie wyrobiska – tablica 1. Opisano metodykę wykonywania pomiarów, a następnie w tablicach 2 i 3 zestawiono wyniki dla wszystkich badanych chodników, podając między innymi wysokość i szerokość danego wyrobiska oraz różnice pomiędzy początkową wartością pola przekroju poprzecznego a wartością wynikającą z pomiarów w rejonie wlotu do ściany (w przypadku ścian przewietrzanych sposobem na „U“) lub około 200 m za czołem ściany (w przypadku ścian przewietrzany sposobem na „Y“). Na rysunkach 3 i 4 przedstawiono pełne przebiegi zaciskania pionowego i poziomego dla wybranych trzech chodników likwidowanych za czołem ścian oraz trzech chodników utrzymywanych za frontem eksploatacji. Średnie procentowe wartości zmniejszenia się pola przekrojów poprzecznych wszystkich badanych chodników przyścianowych, w rejonie wlotów do ścian oraz za frontem eksploatacji, przedstawiono na rysunku 5. W punkcie 3 opisano prognozowanie deformacji chodników z wykorzystaniem modelowania numerycznego Dla przeprowadzenia obliczeń numerycznych wykorzystano program Phase2, bazujący na metodzie elementów skończonych. Scharakteryzowano metodę prognozy zaciskania chodników przyścianowych z wykorzystaniem tego programu, w której jednym z elementów jest zmiana parametrów m_{bz} i s_z w kryterium wytrzymałościowym Hoek'a-Browna, w zależności od odległości frontu eksploatacji. Dla wybranych chodników przyścianowych przygotowano modele górotworu w postaci tarczy o szerokości i wysokości 70 m Modele przygotowano w oparciu o rzeczywiste profile skał otaczających rozpatrywane wyrobiska. Przykłady tych modeli przedstawiono na rysunku 6, zaś na rysunkach 7-9 przedstawiono wybrane wyniki obliczeń numerycznych w postaci map przemieszczeń górotworu wokół wyrobisk. Dokonano oceny dokładności obliczeń numerycznych poprzez porównanie obliczonych wartości pola przekroju poprzecznego chodników, jakie wynikały z prognozy oraz z pomiarów dołowych (Tabl. 4).

Słowa kluczowe: podziemna eksploatacja, chodnik przyścianowy, konwergencja, modelowanie numeryczne

1. Introduction

Once a colliery starts to extract a new longwall panel, a certain level of production is assumed which should enable a quick return of the incurred significant costs and generating profits. Unfortunately, in underground hard coal mining under natural hazards there are a number of limitations concerning the volume of production which may be obtained from a longwall panel. One of the limitations is high level of methane hazard. Out of total hard coal production in Poland of 79.2 million tons in 2012, 75% came from gassy coal seams, i.e. 59.4 million tons. (Krause & Sebastian, 2013). During the time period from 1992-2012, the average depth of mining activity increased in Polish collieries from 539 metre to approximately 710 metre (Konopko, 2013). The increase in the mining depth and, associated with that, constantly deteriorating geotechnical conditions of carboniferous rock mass, expressed as changes in geomechanical parameters of rocks (Bukowska, 2007; 2012) and methane content of coal seams, with a simultaneous increase in concentration of production, results in increased volume of methane flowing into workings (Krause & Sebastian, 2013). Among the natural hazards concurring in Polish collieries, a particular increase in spontaneous fire and methane hazards can be observed. In such mining conditions, in the vast majority of longwalls in Poland, collieries use two main ventilation systems, i.e. "U", which is the dominant one, with the flow of return air along solid coal, and "Y" (in various versions) with the flow of return air behind the longwall face (Krause, 2008; Szlązak et al., 2012). Predominance of "U" system results from the fact that in collieries air flow through gob is limited, which, in turn, lowers the level of spontaneous fire hazard. Another factor in favour of the ventilation system is a difficulty in maintaining one of the gateroads behind the longwall face, which in many cases is problematic. As Krause showed (2004, 2008), when highly gassy coal seams are mined, maintaining adequate dimensions of the gateroads is a significant issue, which determines safety of mining activities. In the longwalls with "U" ventilation system, special attention is paid to the adequate cross-sectional area of a ventilation road. In "Y" ventilation approach, it is important to maintain adequate dimensions of the gateroad, where return air flows behind the longwall face. In the aforementioned papers Krause states that to ensure safe mining in gassy seams, it is necessary to make calculations to forecast gateroad convergence (assess decrease in the cross-sectional area), considering influence of an abutment pressure.

To assess the gateroad convergence and determine the decrease in their cross-sectional area, within the framework of The National Centre for Research and Development (NCBiR) project titled: "Improving Work Safety in Mines", a series of underground measurements were conducted. The paper presents results of vertical and horizontal convergence measured in 28 gateroads, in retreated longwalls. The measurements were carried out in 12 longwalls with "Y" and in 4 longwalls with "U" ventilation systems. For the selected six gateroads (3 longwall gateroads with "U" and 3 with "Y" ventilation approaches) forecast of their convergence was made by means of numerical modeling and a method developed at GIG (Prusek, 2008a). Accuracy of the forecast calculations was assessed through comparing their results with underground measurements.

2. Underground measurements of vertical and horizontal convergence in gateroads

2.1. General characteristics of geological and mining conditions in the analysed gateroads

Underground measurements of changes in the dimensions (height and width) of gateroads were conducted in 28 workings, in seven collieries of Upper Silesian Coal Basin. Basic information on each of the gateroads is presented in Table 1.

TABLE 1

Selected parameters characterising geological and mining conditions in the area of the tested gateroads

Working No.	**Depth, m**	**Uniaxial compressive strength MPa**			**Longwall height, m**	**Longwall width, m**	**Longwall daily advance, m/day**	**Location of gateroad**	**Longwall ventilation system**
		roof	**coal**	**floor**					
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Gateroad 1	1020	48.4	8.4	43.3	2.5	280	2.0	surrounded by unmined coal maintained behind the longwall face	"Y"
Gateroad 2	1020	48.4	8.4	43.3	2.5	280	2.0	goaf on one side – reused, abandoned behind the longwall face	

1	2	3	4	5	6	7	8	9	10
Gateroad 3	1040	39.7	21.8	48.6	2.7	245	2.0	surrounded by unmined coal, closed behind the longwall face	"U"
Gateroad 4	980	39.7	21.8	48.6	2.7	245	2.0	near goaf –coal pillar, closed inby the longwall face	
Gateroad 5	900	43.0	14.0	14.0	3.0	240	start	surrounded by unmined coal, abandoned behind the longwall face	"U"
Gateroad 6	870	43.0	14.0	14.0	3.0	240	start	Near goaf – coal pillar, abandoned behind the longwall face	
Gateroad 7	870	20,2	17.7	43.8	3.5	200	3.0	surrounded by unmined coal, abandoned behind the longwall face	"U"
Gateroad 8	870	20,2	17.7	43.8	3.5	200	3.0	Near goaf – coal pillar, abandoned behind the longwall face	
Gateroad 9	850	46.3	16.9	25.9	2.5	250	2.5	surrounded by unmined coal, maintained behind the longwall face	"Y"
Gateroad 10	820	46.3	16.9	25.9	2.5	250	2.5	goaf on one side - reused and surrounded by unmined coal, abandoned behind the longwall face	
Gateroad 11	980	56.9	14.1	37.4	2.4	145	8.0	surrounded by unmined coal, maintained behind the longwall face	"Y"
Gateroad 12	940	56.9	14.1	37.4	2.4	145	8.0	goaf on one side – reused abandoned behind the longwall face	
Gateroad 13	1110	28.2	15.0	36.0	1.8	235	4.0	surrounded by unmined coal, abandoned behind the longwall face	"Y"
Gateroad 14	1060	28.2	15.0	36.0	1.8	235	4.0	surrounded by unmined coal, maintained behind the longwall face	
Gateroad 15	950	54.1	9.8	55.8	1.7	243	3.5	surrounded by unmined coal, maintained behind the longwall face	"Y"
Gateroad 16	920	54.1	9.8	55.8	1.7	243	3.5	goaf on one side – reused abandoned behind the longwall face	
Gateroad 17	770	42.6	8.9	39.6	2.4	242	3.0	surrounded by unmined coal, abandoned behind the longwall face	"Y"
Gateroad 18	840	42.6	8.9	39,6	2.4	242	3.0	surrounded by unmined coal, maintained behind the longwall face	

1	2	3	4	5	6	7	8	9	10
Gateroad 19	970	55.1	7.6	72.7	2.5	212	start	surrounded by unmined coal, maintained behind the longwall face	“Y”
Gateroad 20	875	55.1	7.6	72.7	2.5	212	start	surrounded by unmined coal, abandoned behind the longwall face	
Gateroad 21	800	41.0	9.1	41.0	2.5	225	2.5	surrounded by unmined coal, maintained behind the longwall face	“Y”
Gateroad 22	625	15.7	24.6	19.4	3.9	310	4.0	surrounded by unmined coal, maintained behind the longwall face	“Y”
Gateroad 23	600	15.7	24.6	19.4	3.9	310	4.0	goaf on one side - reused abandoned behind the longwall face	
Gateroad 24	630	10,5	25.8	28.5	4.0	250	4.0	surrounded by unmined coal, abandoned behind the longwall face	“U”
Gateroad 25	630	10,5	25.8	28.5	4.0	250	4.0	surrounded by unmined coal, abandoned behind the longwall face	
Gateroad 26	290	30,3	16.4	24.2	3.4	120	4.0	surrounded by unmined coal, maintained behind the longwall face	“Y”
Gateroad 27	850	28.0	14.9	33.0	1.9	180	4.0	surrounded by unmined coal, maintained behind the longwall face	“Y”
Gateroad 28	400	20,0	28.1	26.0	1.7	205	4.0	surrounded by unmined coal, maintained behind the longwall face	“Y”

In Table 1, „Location of gateroad“ column (second from the right) contains information on the surrounding of a working. For the longwalls with „U“ ventilation system, there were two variants of working’s location, i.e. the gateroads were either surrounded by unmined coal, or with goaf on one side. For gateroads located with goaf on one side, two groups of the workings were analysed. The first one comprised of reused workings from a neighbouring, previously mined longwall panel (description in the table – “goaf on one side – reused”). The second one comprised of new gateroads driven in the vicinity of gob, with an up to 5 metre thick coal pillar (description in the table – “near goaf – coal pillar”). The analysed gateroads were supported by yielding steel arches, as a primary support. The arches were made from steel V-shaped cross sectional profiles with an elementary mass of 29 or 32 kg/m. The primary support in gateroads was often reinforced with additional components such as: wooden props, steel friction props, steel horseheads bolted with flexible bolts. Additionally, to reinforce the support behind the longwall face, wooden chocks were used. Figure 1 shows examples of gateroad support both ahead of and behind the longwall face.

a) b)

Fig. 1. Examples of a gateroad support where underground measurements of deformation were conducted, a – yielding steel arches, reinforced with steel horseheads bolted with flexible bolts view of the gateroad ahead of the longwall face, b – yielding steel arches, reinforced with wooden and steel props, view of the gateroad behind the longwall face

2.2. Results of underground measurements of vertical and horizontal convergence in gateroads

To assess deformation of the gateroads, exposed to the influence of a retreating longwalls, underground measurements of their height and width were carried out at different distances from the longwall face. The measurements were made in the gateroads with "U" ventilation system along solid coal, at the following distances ahead of the longwall face: 500 m, 300 m, 200 m, 100 m, 50 m, 20 m, 0 m (Fig. 2a). For the longwalls with "Y" ventilation approach, the measurements of height and width of the gateroads were conducted also behind the face, at the distances : 20 m, 50 m, 100 m and 200 m (Fig. 2b). All the measurements were made by means of simple linear devices.

The minimal values of height and width measured in particular measurement points in gateroads are collected in Tables 2 and 3. Table 2 contains results for the gateroads abandoned behind the longwall faces (longwalls with "U" ventilation system), whereas Table 3 shows the results for the entries maintained behind the faces (longwalls with "Y" ventilation approach). The tables, in addition to the minimal values of height and width of workings, contain as well: initial dimensions of workings, initial value of cross-sectional area for each of the gateroads. They also present the calculated value of cross-sectional area based on underground measurements and the percentage of the decrease in cross-sectional area of the gateroads, resulting from their deformation.

Figure 3 shows vertical and horizontal convergence at different distances from the longwall face, for three selected gateroads abandoned behind the faces. In these cases longwall panels were ventilated with "U" system. The selected gateroads were: surrounded by unmined coal (gateroad no. 3), and with goaf on one side (gateroads no. 2 and 4). For gateroads no. 2 and 4, the first one was a newly developed working with an approximately 5-metre-thick coal pillar separating it from the goaf of neighbouring (previously mined) longwall panel. Gateroad 4 was a working which was reused after maintaining it during retreating from a neighbouring longwall panel.

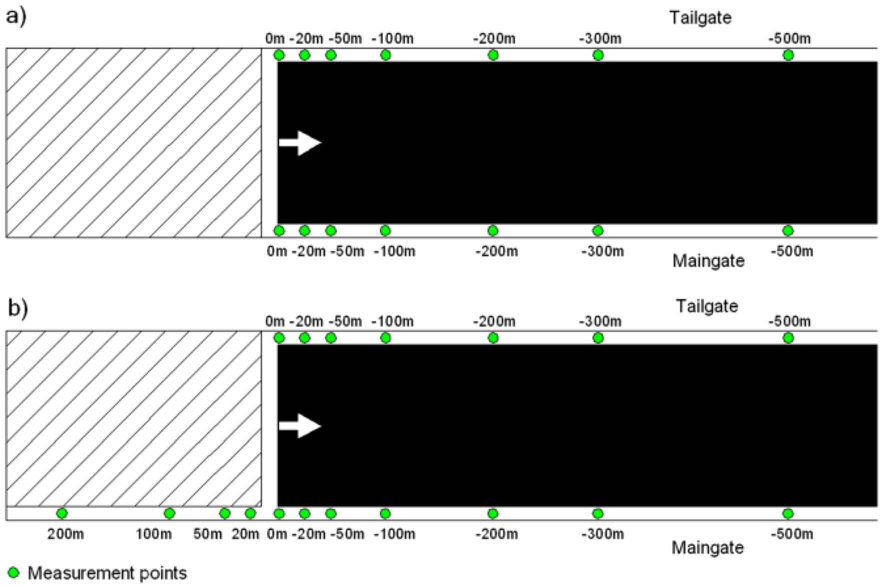


Fig. 2. Location of measurement points in gateroads: a – for the gateroads abandoned behind the longwall face ("U" ventilation system); b – for the gateroads maintained behind the longwall face ("Y" ventilation layout)

TABLE 2

Results of measurements of height and width of gateroads located ahead of the longwall faces with: initial dimensions of workings, initial cross-sectional area of gateroads, calculated cross-sectional area at the longwall face, and decrease in cross-sectional area of a working resulting from convergence

No.	**Working No.**	**Initial dimensions of gateroads Height/Width, mm**	**Initial cross-sectional area of gateroads, m^2**	**Height of gateroad at longwall face, Mm**	**Width of gateroad at longwall face, mm**	**Cross-sectional area of gateroad at longwall face, m^2**	**Decrease in cross-sectional area of gateroad %**
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Gateroad surrounded by unmined coal							
1.	Gateroad 1	3800 / 5500	17.7	3065	5000	13.3	24.6
2.	Gateroad 3	3500 / 5000	14.9	2168	4545	9.4	37.0
3.	Gateroad 5	3800 / 5500	17.7	3200	4868	13.4	24.5
4.	Gateroad 7	3800 / 5500	17.7	2584	3629	8.0	54.7
5.	Gateroad 9	3800 / 5500	17.7	3085	4720	12.5	29.3
6.	Gateroad 11	3800 / 5500	17.7	2218	3933	7.9	55.5
7.	Gateroad 13	3800 / 5500	17.7	3340	4554	12.8	27.7
8.	Gateroad 14	3800 / 5500	17.7	3560	5201	15.7	11.3
9.	Gateroad 15	3800 / 5500	17.7	3095	4784	12.8	28.0
10.	Gateroad 17	3500 / 5000	14.9	3018	4451	11.5	22.5
11.	Gateroad 18	3500 / 5000	14.9	3531	5268	14.8	0,3
12.	Gateroad 19	3500 / 5000	14.9	3520	4440	13.0	12.7
13.	Gateroad 20	3800 / 5500	17.7	3421	5192	15.2	14.2
14.	Gateroad 21	3800 / 5500	17.7	3000	4000	10,1	42.8

1	2	3	4	5	6	7	8
15.	Gateroad 22	3500 / 5000	14.9	3170	4595	12.5	16.4
16.	Gateroad 24	3500 / 5000	14.9	3200	4390	11.9	20,0
17.	Gateroad 25	3500 / 5000	14.9	2846	4131	10,1	32.1
18.	Gateroad 26	3500 / 5000	14.9	2710	4595	11.1	25.8
19.	Gateroad 27	3800 / 5500	17.7	3375	4950	14.2	19.8
20.	Gateroad 28	3800 / 5500	17.7	3210	4952	13.7	22.8
Gateroad with goaf on one side – “goaf on one side – reused”							
21.	Gateroad 2	3800 / 5500	17.7	2200	4150	8.4	52.7
22.	Gateroad 10	3800 / 5500	17.7	2651	4163	9.6	45.7
23.	Gateroad 12	3800 / 5500	17.7	1929	3178	5.5	69.0
24.	Gateroad 16	3800 / 5500	17.7	1943	3165	5.5	69.0
25.	Gateroad 23	3500 / 5000	14.9	1810	3203	5.3	64.2
Gateroad near goaf – “near goaf -coal pillar”							
26.	Gateroad 4	3500 / 5000	14.9	2283	3995	8,2	44.7
27.	Gateroad 6	3800 / 5500	17.7	3700	5400	16.9	4.5
28.	Gateroad 8	3800 / 5500	17.7	2824	2397	5.7	67.6

TABLE 3

Results of measurements of height and width of gateroads at 200 m behind the longwall face with: initial dimensions of workings, initial cross-sectional area of gateroads, calculated cross-sectional area at 200 m behind the longwall face, and decrease in cross-sectional area of a working resulting from convergence

No.	**Working**	**Initial dimensions of gateroads Height/ Width mm**	**Initial cross-sectional area of gateroads, m^2**	**Height of gateroad at 200 m behind the longwall face, mm**	**Width of gateroad at 200 m behind longwall face, mm**	**Cross-sectional area of gateroad at 200m behind the longwall face, m^2**	**Decrease in cross-sectional area of gateroad, %**
Gateroad maintained behind longwall face – changes their location from “surrounded by unmined coal” to “goaf on one side”							
1.	Gateroad 1	3800 / 5500	17.7	1997	3712	6.8	61.5
2.	Gateroad 9	3800 / 5500	17.7	2575	4465	9.8	44.4
3.	Gateroad 21	3800 / 5500	17.7	2500	3700	8.0	54.8

Figure 4 presents horizontal and vertical convergence at different distances ahead of and behind the longwall face, for three gateroads, maintained behind the faces. The longwalls were ventilated with “Y” approach.

Based on results of underground measurements presented in Tables 2 and 3 and in Figures 3 and 4, it may be concluded that convergence in the gateroads differs, which results mainly from the changeable geological and mining conditions in the area of the workings. For longwalls with “U” ventilation system, it can be observed that deformation of the gateroads surrounded by unmined coal was lower in comparison with the workings located with goaf on one side (Table 3). In the whole group of eight gateroads located with goaf on one side, with “U” ventilation pattern, there was a significant horizontal and vertical convergence, both in newly developed gateroads with coal pillars, and reused workings of previously mined longwall panel. In one of the analyzed gateroads (gateroad no. 6, Table 2) its deformation was significantly lower, in comparison with

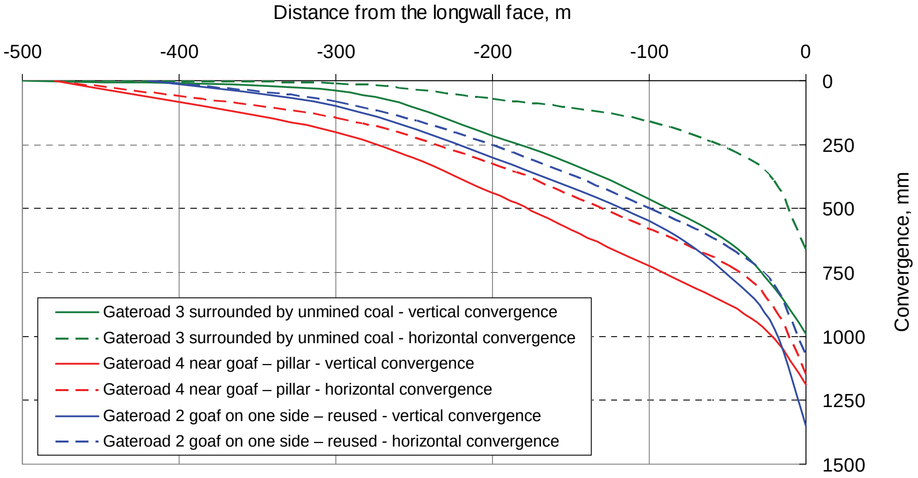


Fig. 3. Horizontal and vertical convergence of gateroads at different distances from the longwall face – gateroads abandoned behind the faces, longwalls ventilated with "U" system

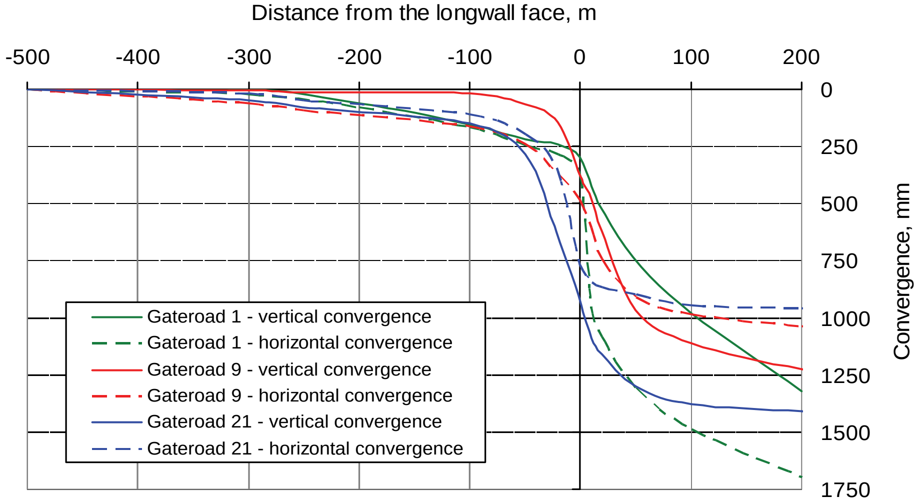


Fig. 4. Horizontal and vertical convergence of gateroads at different distances from the longwall face – gateroads maintained behind the longwall faces, longwalls ventilated with "Y" system

other ones. It was an effect of the fact that underground measurements of convergence were performed in the working, when the longwall retreated only a few metres from the set-up room. In gateroads of longwalls with "Y" ventilation system, increase in vertical and horizontal convergence may be observed behind the longwall face (Fig. 4). All the analysed gateroads retained their functionality and their cross-sectional area at the distance of 200 metre behind the longwall faces varied between 6.8 and 9.8 m^2 (Table 4).

The mean percentage values of the decrease in cross-sectional area of the gateroads at the longwall face line (in the T-junction area), and behind the longwall faces, are presented in graphic form in Figure 5. For the tailgates, in case of newly developed workings with a coal pillar the decrease in cross-sectional area was 56%, and for the reused gateroads reached 60%. Averaging newly driven gateroads, gateroad no. 6 was not considered (Table 3) due to the fact that the longwall retreating was in the initial stage, when deformation measurements of the working were conducted.

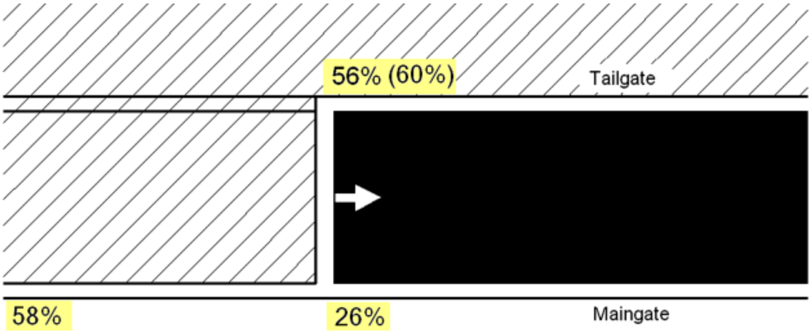


Fig. 5. The mean percentage values of decrease in cross-sectional area of gateroads at the longwall face line (T-junction area) and 200 metre behind the face. For the tailgate with goaf on one side, the first value refers to newly developed gateroads with a coal pillar, the value in brackets refers to the reused gateroads without a coal pillar

3. Forecasted deformation of selected gateroads

In recent years at GIG, as an effect of research several methods have been developed to forecast convergence of gateroads. The methods are based on, among others, empirical relationships, approximate models, neural networks and numerical modeling (Prusek, 2008a, 2010; Prusek & Jędrzejec, 2008). The paper presents results of forecasting gateroad convergence by means of numerical modeling. The forecasts were prepared for three selected gateroads of longwalls with "U" ventilation system, and three workings of longwalls with "Y" approach. Their convergence is presented in Figures 3 and 4.

3.1. Numerical calculations of gateroad deformation

Numerical calculations of gateroad deformation (convergence) were performed by means of Phase2 software based on the finite element method (FEM). Scientists in Poland and abroad use the program for calculating gateroad convergence (Majcherczyk & Małkowski, 2009; Toraño et al., 2002). In the calculations Hoek-Brown strength criterion was assumed, which, for cracked rock mass, is presented by the following equation (Tajduś et al., 2012; Hoek, 2006):

$$\sigma'_1 = \sigma'_3 + \sigma_{ci} \left(m_b \frac{\sigma'_3}{\sigma_{ci}} + s \right)^a \text{ , MPa} \tag{1}$$

where:

σ_1' and σ_3' — effective maximal and minimal stress during failure, MPa,
m_b — value of Hoek-Brown parameter for rock mass,
s and a — parameters, determined basing on rockmass properties,
σ_{ci} — uniaxial compression strength of a rock sample, MPa.

The method of calculating gateroad convergence developed at GIG with Phase2 software, to reflect influence of abutment pressure, assumes corresponding lowering strength and deformation properties of rocks surrounding a working. The properties are lowered through modifying post-failure parameters m_{bz} and s_z in Hoek-Brown equation. For different rocks the parameters are calculated with the following relationships (Prusek, 2008b):

– for coal:

$$m_{bz} = 0.6278 \cdot e^{-0.0024 \cdot d}, \quad s_z = 0.000494 \cdot e^{-0.00393 \cdot d} \tag{2}$$

– for mudstone:

$$m_{bz} = 0.3197 \cdot e^{-0.0148 \cdot d}, \quad s_z = 0.00041 \cdot e^{-0.01592 \cdot d} \tag{3}$$

– for sandy shale:

$$m_{bz} = 0.5093 \cdot e^{-0.0127 \cdot d}, \quad s_z = 0.000762 \cdot e^{-0.01881 \cdot d} \tag{4}$$

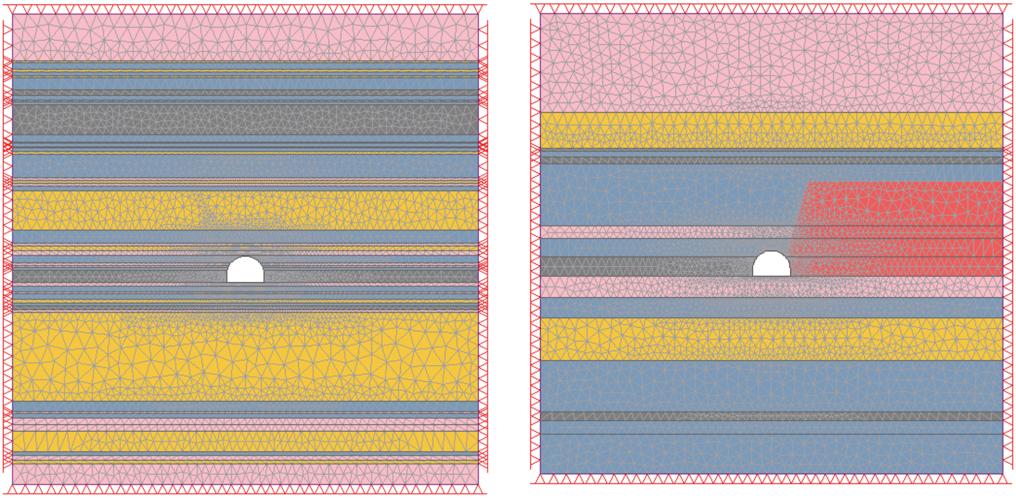
– for sandstone:

$$m_{bz} = 0.7568 \cdot e^{-0.0127 \cdot d}, \quad s_z = 0.001647 \cdot e^{-0.01697 \cdot d} \tag{5}$$

where: d — distance from the longwall face (assumes negative values ahead of the longwall face, and positive behind the longwall face).

Rock mass models were prepared to determine gateroad deformations. They were plate shaped, 70 metre long and high, where the type of rocks surrounding a working reflected real geological profiles received from the collieries. For each gateroad maintained behind the longwall face, two models were prepared reflecting the situation ahead of and behind the longwall face. Figure 6 presents two selected rock mass models, made for gateroad no. 1 ahead of the longwall face, and gateroad 9, behind the face.

Values of basic parameters of rock layers, including the ones describing Hoek-Brown criterion, were assumed basing on results of the rock mass strength tests and analytical calculations conducted by means of RocLab software (Hoek, 2006). Moreover, for all the analysed models the following assumptions were made: no displacements on the horizontal and vertical edges of the model plate; rock mass is a plastic and isotropic medium, primary stresses result from the depth of workings and mean volumetric weight of the overburden. In all the prepared models basic components of support in the workings were considered, like: steel arches, roof bolts, steel and timber props, and wooden chocks. To model steel arches, “liners” type support (in form of beams) was employed. The elements were attributed to parameters of a V -shaped steel profile, which the arches are build of. The reinforcements to the arches in gateroads, in form of steel



a) b)

Fig. 6. Model of rock mass around gateroads: a) gateroad no. 1 ahead of the longwall face, b) gateroad no. 9 behind the longwall face

props and timber props, and wooden chocks were also modelled in form of “liners” type beam elements, which were attributed to material parameters of steel and wood (Walentek, 2010). To model roof bolting ready bolt elements, available in Phase2 software, were used.

Examples of results of numerical calculations of the gateroad deformation are presented in Figures 7 to 9 in form of rock mass displacement, for the selected three gateroads. Gateroads 2 and 4 presented in Figures 7 and 8 played a role of ventilation roads for longwalls with “U” ven-

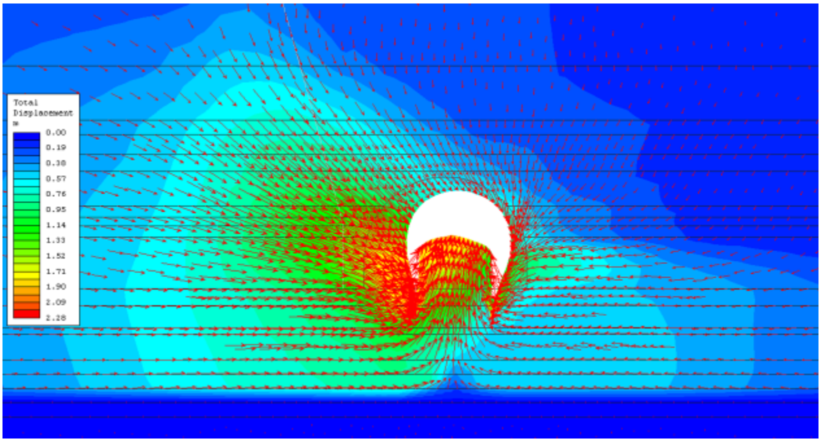


Fig. 7. Rock mass displacement around gateroad 2 at the longwall face line (T-junction area), “U” ventilation system. Gateroad reused, located with goaf on one side and abandoned behind the longwall face

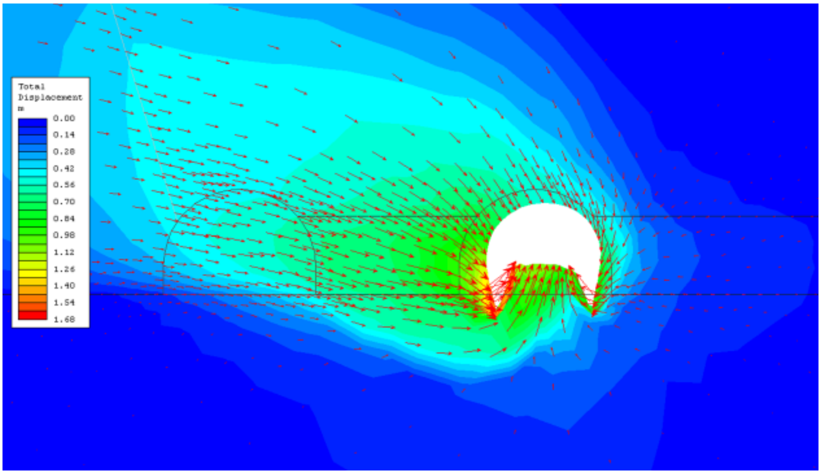


Fig. 8. Rock mass displacement around gateroad 4 at the longwall face line (T-junction area), "U" ventilation system. Newly developed gateroad, located with goaf on one side with a coal pillar, and abandoned behind the longwall face

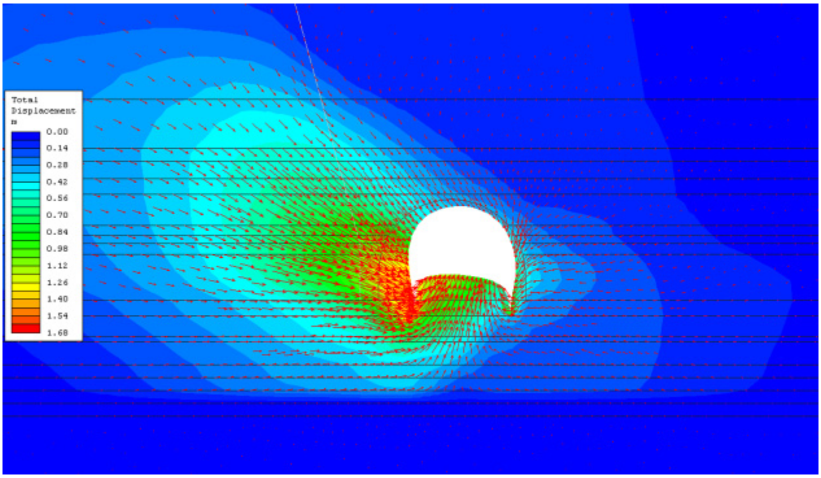


Fig. 9. Rock mass displacement around gateroad 1 at the distance of 200 m behind the longwall face, "Y" ventilation system

tilation system. The gateroads were located with the goaf on one side. Gateroad 2 was a reused working of the neighbouring, previously mined longwall panel, while gateroad 4 was a newly developed one, separated from goaf with a 5-metre-thick coal pillar. Figure 9 shows rock mass displacement around gateroad 1 at the distance of 200 metre behind the longwall face, with "Y" ventilation approach.

3.2. Comparison of results of numerical calculations and underground measurements of gateroad deformation

To assess accuracy of forecasting gateroad deformation with the use of numerical modeling, results of calculations and underground measurements, were compared. Based on numerical simulations and underground measurements of gateroad deformation, values of cross-sectional area of the workings were calculated. For the longwalls with "U" ventilation system the calculations of cross-sectional area of gateroads were made at the longwall face line (T-junction area). For the gateroads in longwalls with "Y" ventilation pattern, cross-sectional area of workings was calculated at the distance of 200 m behind the longwall face. Results of the calculations are presented in Table 4.

TABLE 4

Compared values of cross-sectional area of gateroads, calculated basing on numerical modeling and underground measurements

Longwall ventilation system	**Gateroad no.**	**Initial cross-sectional area of gateroads, m^2**	**Calculated minimal cross-sectional area of gateroad, m^2**		**Difference, %**
			Basing on measurements underground	**Basing on results of numerical modeling**	
"U"	Gateroad 3	14.9	9.7	9.4	+3.1
	Gateroad 4	14.9	8.2	8.7	–6,1
	Gateroad 2	17.7	8.4	6.8	+19.0
"Y"	Gateroad 1	17.7	6.8	7.6	–11.8
	Gateroad 9	17.7	9.8	9.2	–6.1
	Gateroad 21	17.7	8.0	8.2	–2.5

Analysing the values presented in Table 4 it can be concluded that the cross-sectional area of gateroads calculated based on the results of numerical modeling, are considerably similar to the measured values. Percentage differences between the cross-sectional areas of gateroads obtained from the forecast and the underground measurements is between 2.5% and 19%. In two cases (gateroads 3 and 2) deformation of the workings was overestimated, while in case of four gateroads (nos. 1, 4, 9, 21) results of the numerical calculations showed smaller gateroad convergence, than was actually measured.

4. Summary

In Poland underground hard coal extraction goes deeper and deeper, in still worsening geological and mining conditions, and with increasing natural hazards. Additionally the hazards increase because of multiple seam mining. The coal seams are often mined close to each other, resulting in their relaxation and increased outflow of methane into the longwall panels. Such a situation may also cause increase in spontaneous fire hazard if coal gets into the goaf. When methane and fire hazards coexist the latter becomes the dominant one. Therefore, in majority of Polish collieries, the longwall panels are ventilated with "U" system (approximately 75% of longwalls). Considering fire hazard, this system is better, but taking into account methane hazard, is worse. The second ventilation method employed in longwall panels is "Y" approach. This system is favourable, considering methane hazard, yet results in an increase in spontaneous fire hazard in goaf, because the return air flows behind the longwall face, passing the goaf in the maintained gateroad. Both in "U" and "Y" methods, safe and efficient mining under methane hazard conditions and fire hazard depends profoundly on the cross-sectional area of gateroads. That is why, within the framework of The National Centre for Research and Development (NCBiR) project titled: "Improving Work Safety in Mines" underground measurements of deformation were conducted in 28 gateroads. The measurements showed that in the gateroads surrounded by unmined coal, just ahead of the longwall face, their cross-sectional area decreased averagely by 26%. In the gateroads located with goaf on one side, just ahead of the longwall face, there were significantly bigger deformations, and their cross-sectional area decreased by 56% in newly developed workings (with coal pillars) and by 60% in reused workings from the neighbouring, previously mined longwall panel. The gateroads maintained behind the longwall faces ("Y" ventilation system), changing their location from "surrounded by unmined coal" into "goaf on one side", lost approximately almost 60% of the cross-sectional area (measured at 200 m behind the longwall face).

The forecasts of gateroad convergence performed by means of numerical modeling gave satisfying results. The difference between the values of gateroad cross-sectional area, obtained from numerical calculations and the underground measurements, did not exceed 20%. The presented method of forecasting gateroad deformation may be used in designing dimensions and the type of support in the gateroads. For certain geological and mining conditions, when highly gassy coal seam is planned to be mined with the longwalls ventilated with "U" approach, it is advised to assess the decrease in gateroad cross-sectional area, caused by the influence of abutment pressure during longwall panel retreating.

References

Bukowska M., Sanetra U., Wadas M., 2007. *The post-peak failure properties and deformational structures of rocks under conventional triaxial compression conditions*. Arch. Min. Sci., Vol. 52, No 3, p. 297-310.

Bukowska M., Sanetra U., Wadas M., 2012. *Chronostratigraphic and depth variability of porosity and strength of hard coals of Upper Silesian Basin.* Mineral Resources Management, Vol. 28/4, 151-166.

Hoek E., 2006. *Practical Rock Engineering*. Rocscience Inc, www.rocscience.com.

Konopko W., 2013. *Raport roczny o stanie podstawowych zagrożeń naturalnych i technicznych w górnictwie węgla kamiennego.* Praca zbior. pod red.: W. Konopko. Wydaw. GIG, Katowice, s. 7-16.

Krause E., 2004. *Wpływ przekroju wyrobisk przyścianowych na warunki wentylacyjno-metanowe*. XI Międzynarodowa Konferencja Tąpania 2004, Wyd. GIG, Katowice, s. 153-157.

Krause E., 2008. *Wpływ przekroju wyrobisk przyścianowych na kształtowanie się zagrożenia wentylacyjno-metanowego w rejonach ścian*. Bezpieczeństwo Pracy i Ochrona Środowiska w Górnictwie, Miesięcznik WUG, nr 1, s. 22-26.

Krause E., Sebastian Z., 2013. *Zagrożenie gazowe. Raport roczny o stanie podstawowych zagrożeń naturalnych i technicznych w górnictwie węgla kamiennego*. Praca zbior. pod red.: W. Konopko. Wydaw. GIG, Katowice, s. 30-43.

Majcherczyk T., Małkowski P., 2003. *Wpływ frontu ścianowego na wielkość strefy spękań wokół wyrobiska przyścianowego*. Wiadomości Górnicze, nr 1/2003, Katowice.

Prusek S., 2008a. *Metody prognozowania deformacji wyrobisk w strefach wpływu eksploatacji z zawałem stropu*. Prace Naukowe GIG, nr 874, Katowice.

Prusek S., 2008b. *Modification of parameters in the Hoek-Brown failure criterion for gate road deformation prediction by means of numerical modeling*. Glückauf, No. 9, s. 529-534

Prusek S., Jędrzejec E., 2008c. *Adjustment of the Budryk-Knothe theory to forecasting deformations of gateroads*. Arch. Min. Sci., Vol. 53, No 1, p. 97-114.

Prusek S., 2010. *Empirical-statistical model of gate roads deformation*. Arch. Min. Sci., Vol. 55, No 2, p. 295-312.

Szlązak N., Obracaj D., Borowski M., 2012. *Systemy wentylacji wyrobisk ścianowych w kopalniach węgla kamiennego*. Referat w pracy zbior. pod red.: S. Pruska, J. Cygankiewicza, pt. Nowe spojrzenie na wybrane zagrożenia naturalne w kopalniach. Wydaw. GIG, Katowice, str. 175-186.

Tajduś A., Cała M., Tajduś K., 2012. *Geomechanika w budownictwie podziemnym. Projektowanie i budowa tuneli*. Wydawnictwa AGH, Kraków.

Toraño J., Rodríguez Díez R., Rivas Cid J.M., Casal Barciella M.M., 2002. *FEM modeling of roadways driven in a fractured rock mass under a longwall influence*. Computers and Geotechnice, No. 29/2002, s. 411-431.

Walentek A., 2010. *Oddziaływanie frontu eksploatacji na zasięg strefy spękań wokół chodników*. Prace Naukowe GIG. Kwartalnik Nr 2/1, Katowice, s. 315-329.

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