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Mining exploitation of hard coal seams by galleries and surface deformations

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Abstract
Nowadays, in the Upper Silesian Coal Basin, in addition to high-performance longwall systems, roadway mining is conducted in several mines, leaving pillars of coal between roadways. This is particularly applicable in the old mines where the residue of hard coal deposits, left in the protective pillars of mine shafts or other facilities, is exploited. The article presents the mining process carried out with a single gallery in three seams and grouped in plots and consequent surface deformations. Extraction galleries were 5.6 m wide and 3.8-4.3 m high. Coal pillars with an average width of 12 m were left in plots between galleries. Decommissioning of galleries was carried out by filling them with hydraulic backfill from waste (dust) from the power plant. The width of the coal pillars was determined depending on the level of protection required to secure objects on the surface properly.
In seams, where single galleries were used, the exploitation factor ranged from 0.05 to 0.25 (!), and 0.21. above the extraction plots. The value of exploitation factor, as well as rock mass (tgβ as in Knothe-Budryk theory), is significantly influenced by remains (old excavations) that were activated by new exploitation. The obtained results were confronted with the Polish and world underground coal mines.

Keywords
Mining exploitation by galleries, surfaces deformation, deformation measurements, discussion

Introduction

Extraction of remains of seams is conducted in some partly decommissioned hard coal mines in Poland. Such deposits are located most often in the protective pillars of inactive shafts allowing to retrieve the remaining resources without any investments. However, when objects on the surface or mine shafts are protected, their protection must be maintained. In such cases, partial exploitation is conducted, i.e. exploitation where part of the mined deposit remains. For example, operation based by belts, room-and-pillar or by galleries. This is still a current problem in Polish hard coal mining.

The purpose of the article is to present the results of surface deformation caused by exploitation by galleries in the protective pillar of the decommissioned shaft and active facilities on the surface of the coking plant and high chimney (113m), Figure 1. In particular, the determined values of the exploitation coefficients (a), which is the quotient of the maximum lowering of the surface (wmax) by the thickness of the exploited seam (g). This is the basic parameter of the theory of rock mass movements and surface by Knothe-Budryk (Knothe 1984).

Mining exploitation was carried out in three hard coal seams with individual and grouped galleries, which formed exploitation plots. The plot has comprised a group of galleries (4-8) located in parallel, separated by coal pillars.

Partial exploitation had already been carried out in Poland and in the world. Polish research concerns exploitation carried out by belts with hydraulic backfill and left pillars conducted in the 1950s and 1960s (Knothe, 1958); (Trojanowski, Wajdeczko, Pytlarz, 1965). After 2000 the mining process was based on galleries which gave new research opportunities (Polanin, Kowalski, Walentek, 2019; Kowalski, 2019).

Figure 1. Coking plant and high chimney under which partial operation was carried out

Partial mining in hard coal mining in the world has been conducted for a long time (SEH, 1975), and American mining still uses a room-and-pillar system, which gives almost half of total extraction (Whittaker and Reddish, 1989) (Magers, 1993). In the room-and-pillar system, exploitation consists of drilling exploitation galleries in directions perpendicular to each other, thus creating a grid of coal pillars. Excavations are mined in a rectangular cross-section with a shearer type "continuous miner", and independent anchor support is used to secure them. A similar system has been used in recent years in Czech mining, where the mining was carried out at a depth of over 800 m (Hudeček et al., 2017; Waclawik, Snuparek, Kukutsc, 2017).

In the last few years, implementation of the technology of partial exploitation of exploitation galleries with backfilling (Roadway Backfill Coal Mining, RBCM) has been undertaken in Chinese hard coal mines in Shaanxi Province (Zhang et al., 2016).

Partial exploitation and the exploitation factor

When conducting partial exploitation in Poland by belts with hydraulic backfill and using a deposit of 50-60%, it was possible to obtain a very low exploitation factor of 0.014 to 0.026 (Knothe, 1958); (Trojanowski, Wajdeczko, Pytlarz 1965).

New Polish operation based on gallery exploitation and leaving 4.0 m wide coal pillars between exploitation galleries resulted in exploitation factor values as much as 0.4 (!). This indicates that the remaining coal pillars were too narrow, and this led to the destruction of the pillars and greater roof deflection of exploited seams (Gruchlik, Kowalski, Rajwa, Walentek 2014) (Polanin, Kowalski, Walentek 2019). The galleries were 3.8 m high, 5.6 wide, and the depth of exploitation ranged from 270 m to 400 m. The use of the deposit was about 58%. It was a mining region with similar geological and mining conditions located about 1.0 km north of the area analysed in this article.

Based on experience from English mines (SEH 1975), a nomogram was developed for determining the width of coal pillars depending on the height and the width of excavations and the depth of exploitation, Fig. 2.

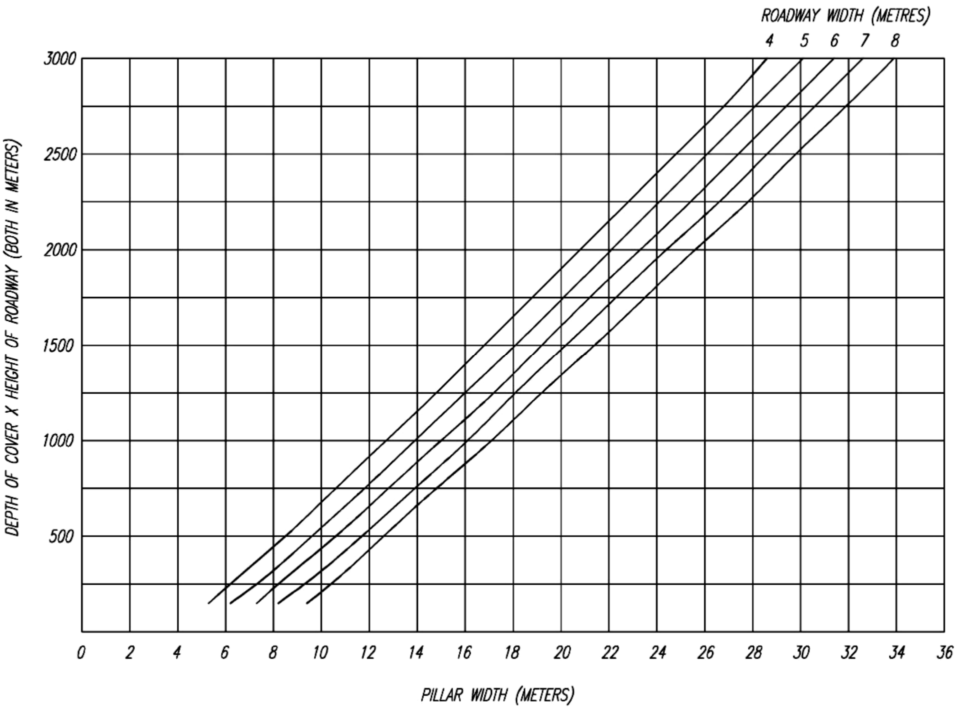

Fig. 2. Nomogram for determining the width of coal pillars (SEH 1975)

The publication (Whittaker and Reddish, 1989) includes later English research, including examples of geological and mining data and determined operational coefficients for operation by belts (short walls 27-73 m long) and coal pillars 32 to 110 m wide and 110 to 823 m deep. The determined operational coefficients were 0.03 to 0.16. The commentary stated that this result was obtained assuming that the width of the coal pillar cannot be smaller than H/4, where H refers to the depth of exploitation.

The American research (Magers, 1993) shows that when operating at low depths (from 30 to 210 m), the value of the exploitation factor depends mainly on the degree of deposit utilisation and ranged from 0 to 0.43 and using the deposit from 44% to 69%. The value of the coefficient is significantly affected by the depth of exploitation; the shallower mining, the greater the exploitation factor.

The results from the operation of galleries and backfilling in Chinese mining are very promising (Zhang et al., 2016). With experimental exploitation of the 5.35 m thick seam at a depth of 130 m and securing excavations with anchor support and their backfilling with a backfill made of sand, loess and binding materials, a very low exploitation factor below 0.01 (!) was obtained. The deposit utilisation rate, in this case, was as much as 70%.

In addition to the presented values of exploitation coefficients in Poland, the principles of theoretical dimensioning of coal pillars have been developed from the point of view of surface protection (Tajduś, Misa, Sroka, 2012, Jiang et al., 2020) and (Sroka and Zespół, 2015). In global mining, coal dimensioning uses analytical methods (Salamon, 1967), (Whittaker and Smith, 1987), (Whittaker and Reddish, 1989), and recently also numerical (Zu, He, Zhang, Yang, 2018).

In the area of surface protection, Polish and world mining experiences differ, mainly in terms of geological conditions and technology of extraction.

Forecast, method of operation and its course, and results of measurements of surface deformations

Geological and mining conditions

Figure 3 shows the geological cross-section W-E through the protective pillar of the decommissioned shaft, in the area of which the coking plant and chimney 113 m high are located on the surface. A fault zone runs 20 m to the east through the pillar. Carboniferous layers fall northeast, with an inclination of 5÷7°. The pavement exploitation project concerned three seams which are 507, 509 and 510. The deposition depth ranged from 240 m (seam 507 in the southwest) to 300 m (seam 510 in the northeast). Seam thickness ranged between 4.5÷5.0 m.

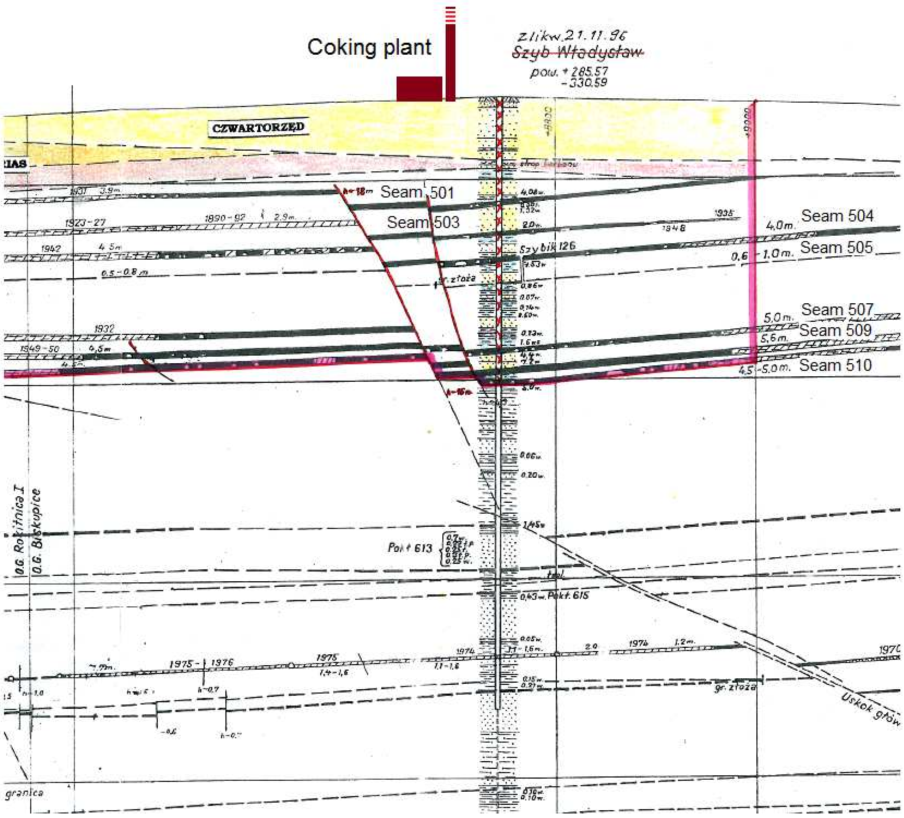

Figure 3. The geological cross-section in the pillar of the decommissioned shaft

Earlier, the hard coal deposit was mined outside the pillar with dry and hydraulic backfill for a total thickness of about 20-24 m at a depth of 120 m seam 501 to 300 m seam 510. Then, in the 1970s, within the protective pillar, a 620 seam 1.8-2.0 m thick was exploited at a depth of about 600 m, Figure 3.

Method of forecasting surface deformation and determining the width of coal pillars

In order to protect the coking plant and high chimney facilities, mining operations were planned by individual galleries, as well as a group of galleries that would form exploitation plots in 509 and 510 seams. Maintenance galleries were assumed to be with a width of 5.6 m and a height of 3.8-4.0 m and will be selected using roadheaders and with an arch and yielding support made of V29 profile as protection. These arch supports will be built at a distance of 1.3 m. The drilling of a new excavation, the next gallery, should be started after backfilling the previously exploited one.

The research team in the first stage of the exploitation design methodology consisted searched for such a lowering of the seam's roof, determined by subsequent numerical tests, that would allow to determine the exploitation factor and then, in the second stage, using the Knothe-Building theory to prepare a surface deformation forecast. Coal pillars were to ensure the stability of excavations and protect objects on the surface that were assessed to be resistant to deformations of at most I category of mining area (Kwiatek ed., 2000).

Simulation of lowering the seam's roof was performed using the numerical method (Finite Element Method) and the Phase2 program created by Rocscience (Kowalski and Walentek, 2013). It was assumed that the rock mass is a transversally isotropic medium. In addition, it was assumed that:

– the rock mass is an elastic-plastic centre,
– there is no possibility of displacement on the horizontal and vertical edges of the model face,
– primary stresses result from the excavation depth of 300 m and the average volumetric weight of the output,
– 50% increase in the value of the load applied to the model caused by the impact of the after-mining edge produced in the seams and closed gallery drifts,
– increased susceptibility of the filling material, taking into account the possibility of the so-called filling zero resulting from the technological process.

Figure 4 shows a numerical model of the rock mass in the form of a disk with a width of 200 m and a height of 150 meters, where the layout and type of rock were adopted according to the geological cross-section of the analysed region.

The result of the numerical forecast of lowering the seam's roof for operation with galleries for coal pillars for the width of 4.0 and 14.0 m is shown in Figures 5 and 6, respectively.

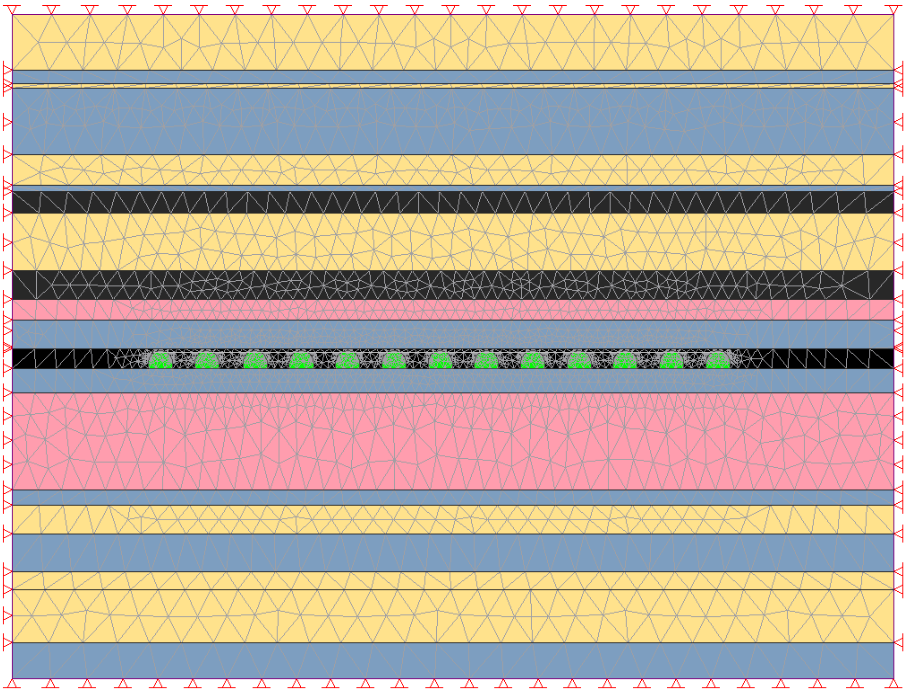

Figure 4. Model of the rock mass: coal pillar 4.0m and extraction galleries 5.5 m

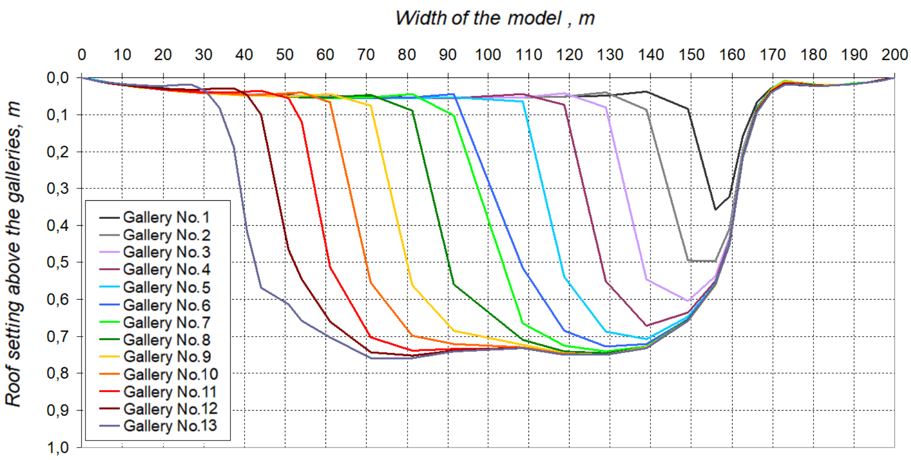

Figure 5. Lowering the seam's roof above the galleries for 4.0 m wide coal pillars

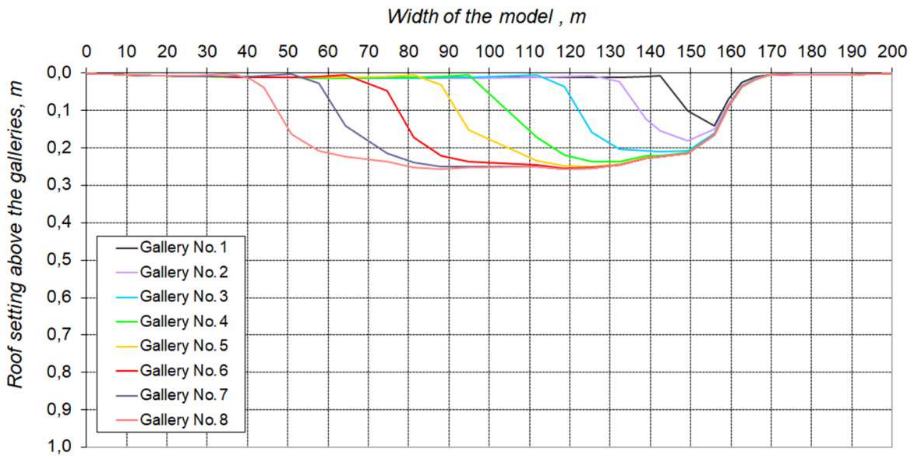

Figure 6. Lowering the seam's roof over the galleries for 14.0 m wide coal pillars

The forecast shows that the modelled maximum roof depression will be for pillars with a width of 4.0 m - 0.75 m, and for pillars with a width of 14 m - 0.25 m, for the height of the exploited seam equal to 3.8 m, which causes the service factors will be 0.2 and 0.07, respectively.

The second parameter of Knothe-Budryk theory tgβ =1.0 was adopted on the basis of research (results of lowering measurements) from exploitation previous operated in the vicinity (Gruchlik, Kowalski, Rajwa, Walentek, 2014).

The largest forecasted decreases in the terrain surface caused by the exploitation of one seam (for a group of plots) and 14.0 m wide pillars were 120-130 mm; the other deformation rates were on the order of half of those corresponding to the first category.

Exploitation conducted by galleries in seams

Figures 7 to 9 shows the scope of the operation carried out with individual galleries in seams 507, 509 and 510 and by exploitation galleries (plots) in seams 509 and 510.

The order of operation was as follows:

- in 2013 and 2014, single galleries were exploited in seam 509 in the eastern part of the pillar and in seam 510 in the western part,
- in 2015 and 2016, pavements in two plots in 509 seam in the western part and in two plots in 510 seam in the eastern part,
- from 2016 to 2019 (end in the first quarter) the 507 seam was exploited only with individual galleries.

The height of galleries in 509 and 510 seams reached 3.8 m, and width reached 5.6 m. The galleries in seam 507 were 4.3 m high 5.6 m wide, and the average width of coal pillars was 12.0 m. The deposit utilisation rate in plots ranged from 29% in seam 509 to 33% in seam 510. Depth of operation ranged from 240 to 300 m.

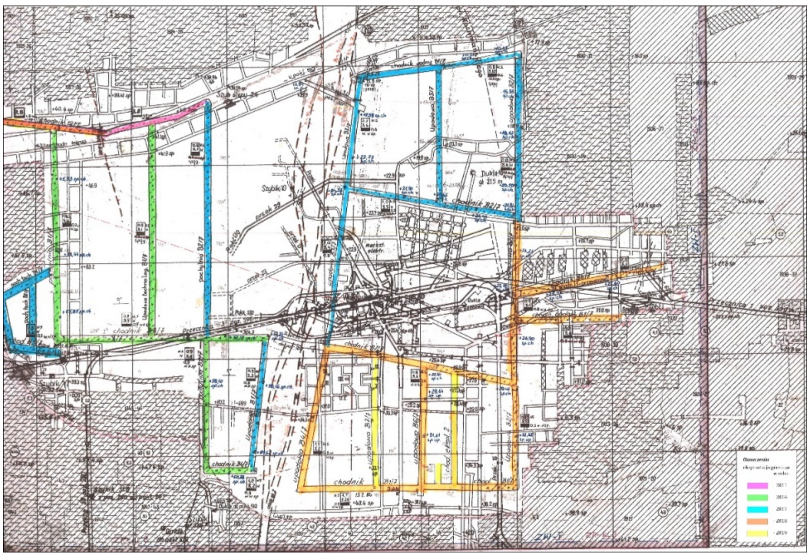

Figure 7. Exploitation by galleries in seam 507

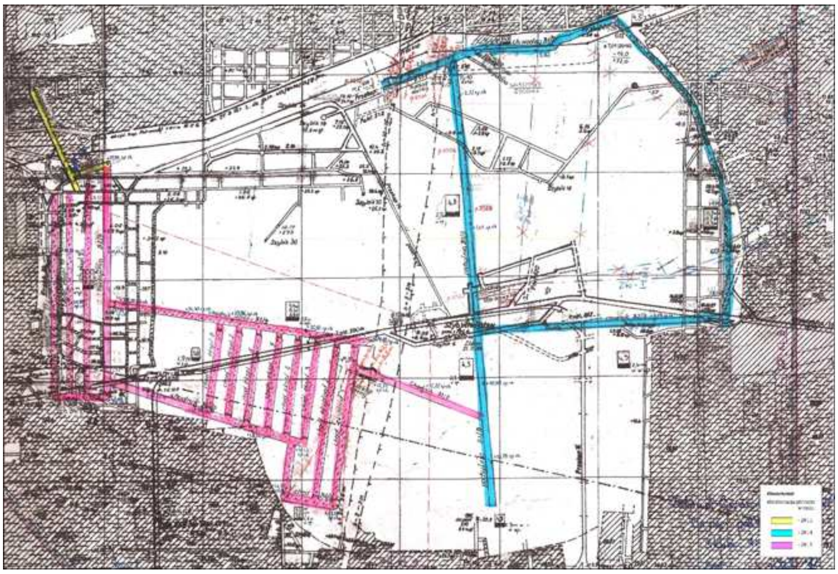

Figure 8. Exploitation based on technological galleries in seam 509 (blue - operational galleries, red - plots)

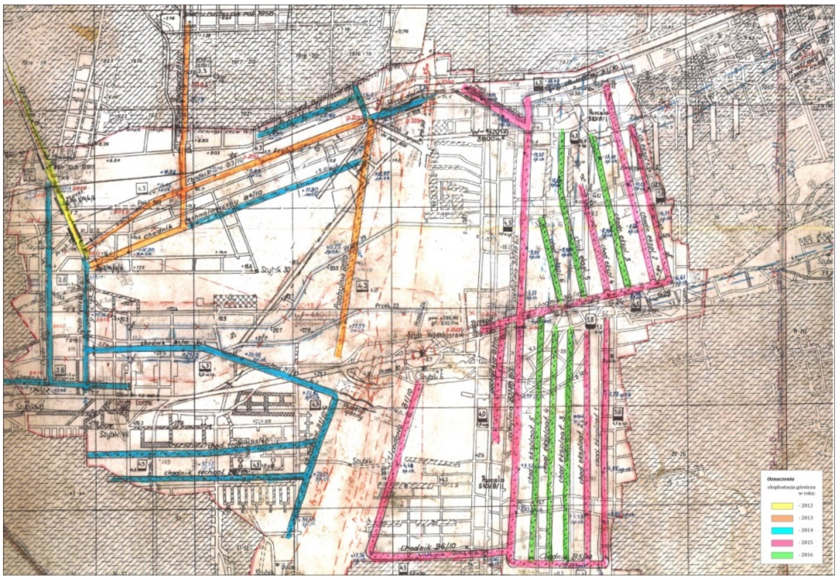

Figure 9. Mining by exploitation galleries in seam 510 (green and red - plots)

Results of measurements of surface deformation

To monitor the deformation of surfaces and building objects, geodetic measurements of depressions were made on buildings (dispersed points) and on 4 measuring lines, on which depressions and segmental horizontal deformations were measured. Figure 10 shows the location of the measurement network, contours of plots (operational pavements) and individual pavements.

Figure 11 shows the isolines of the measured depressions for the period from the first measurement (September 2012) to the last, 14^{th}, (May 17-18, 2019), which shows that there were two basins, one in the southwest with a reduction to 300 mm the other in the north-east, reduced to 500 mm. The extreme inclination of the north-eastern basin derived from the isolines of depressions and was 3.0 mm/m. Fig. 10 shows the measured and theoretically calculated (a posteriori) depressions along line No. 1 for the exploitation of seams 507, 509 and 510.

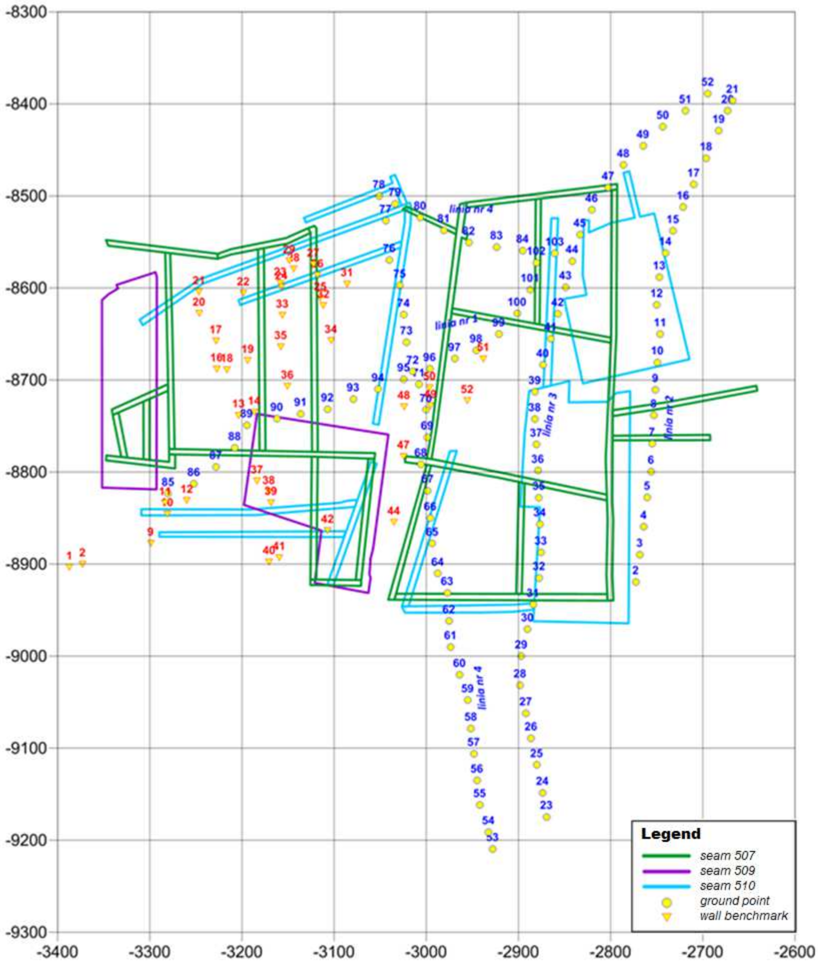

Figure 10. Measuring network, plots and individual galleries

Table 1 lists the values of extreme measured reductions and horizontal deformations on measuring lines and reductions in a group of dispersed points for the period from the beginning (from September 2012 to May 2019).

Tab. 1. List of measured extreme deformation rates

Measurement lines, group of points	The largest decrease, [m]	Horizontal deformation, [mm/m]
No.1	0.182 – 0.498	-1.3 – +1.4
No.2	0.419	-1.8 – +0.6
No.3	0.499	-2.0* – +1.2
No.4	0.486	±1.5
Group of points	0.329	

Table 1 shows that the extreme indicators with respect to horizontal deformations were on the border of mining categories I and II, similar to the inclinations.

On the other hand, Fig. 12 shows the isolines of the depressions from December 2016 to May 2019, which correspond to the operation of 507 seam by single galleries. Fig. 12 presents a significant differentiation of depressions in the western and eastern part. In the western part the increase in depression is up to 100 mm, and the north-eastern part up to 260 mm, which is mainly related to old excavations, Figures 7 and 9.

A posteriori of the values of exploitation coefficients were determined using the formulas of Knothe-Budryk theory (Knothe, 1984) for a complete assessment of the impact of mining operations on surface deformations.

The calculated values of the coefficients, by the method of least squares, caused by the operation of 507, 509 and 510 seams are:

– for exploitation plots $a = 0.21$.
– for exploitation galleries in the eastern part $a = 0.07$-0.25 and in the western part $a = 0.05$.

The rock mass parameter ranged from $tg\beta = 0.6$ to $tg\beta = 1.0$.

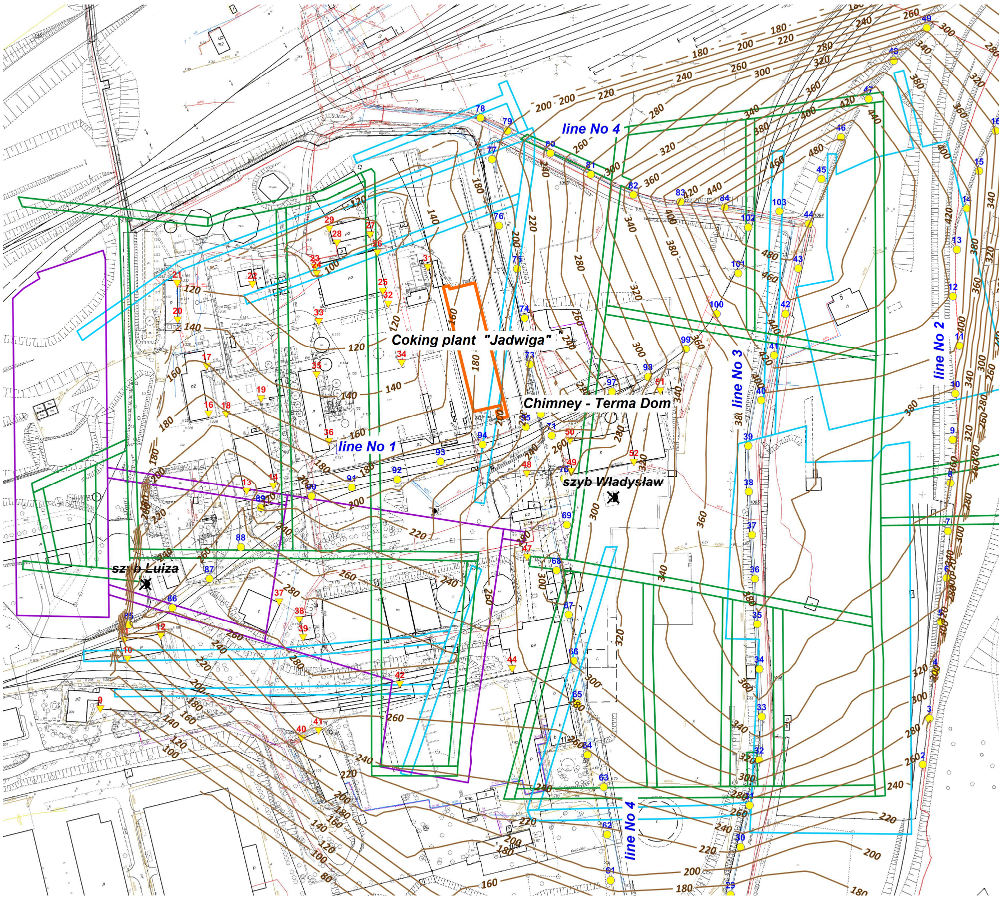

Figure 11. Isolines of measured surface depressions for the period from September 2012 to May 2019

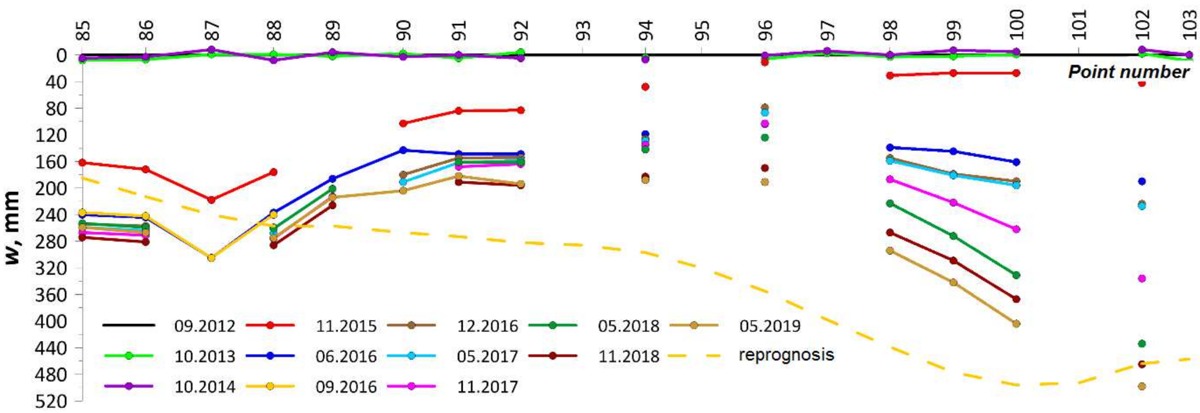

Figure 12. The depressions along line 1 for the exploitation of 507÷510 seams measured and theoretically calculated

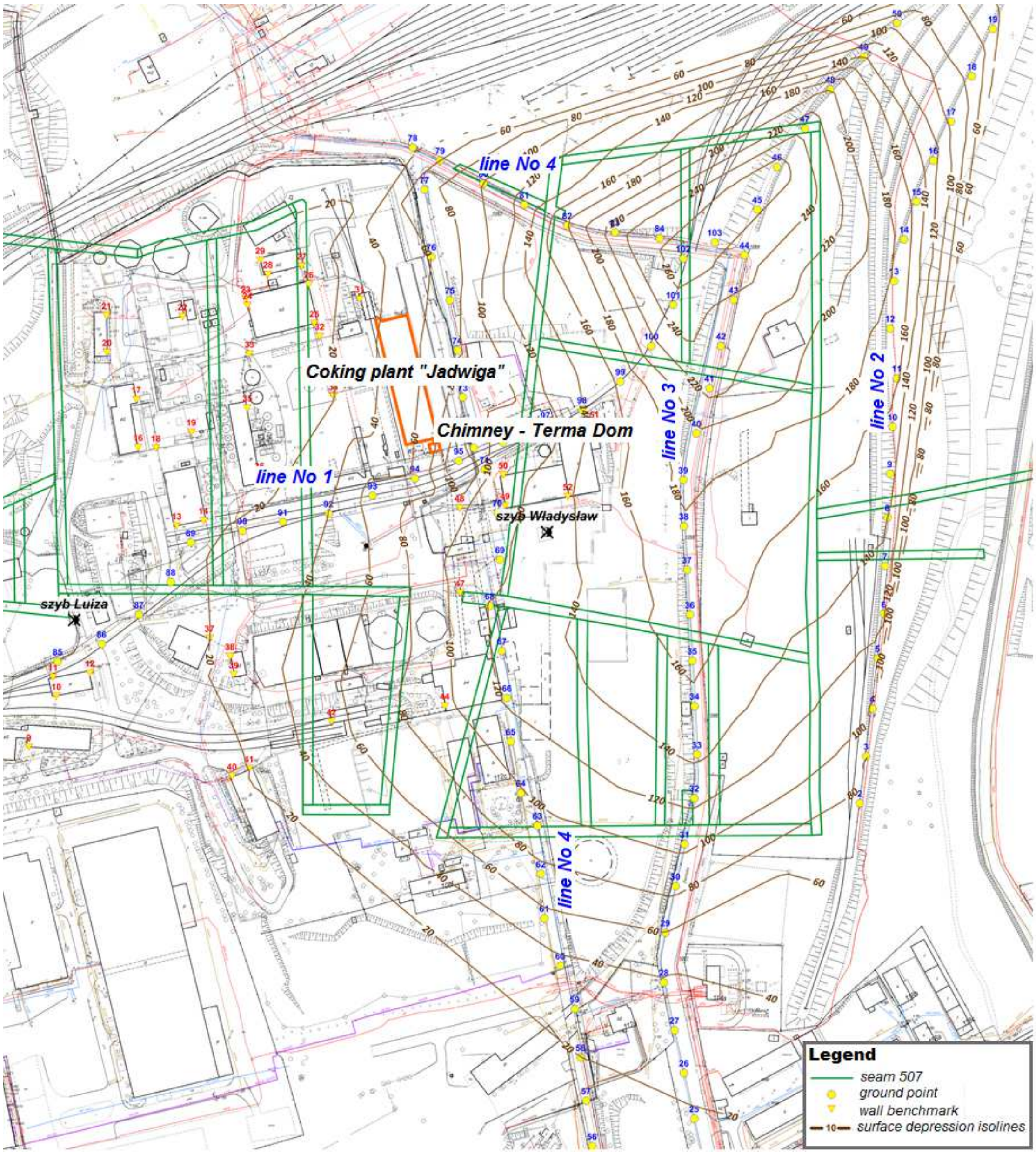

Figure 13. Isolines of measured surface depressions for the period from December 2016 to May 2019, corresponding to operation in seam 507

Discussion of measurement results and methods for determining the width of coal pillars

Table 1 and Figures 11-13 indicate that:

- The values of the measured maximum depressions in the west and east differ significantly. They are 300 mm and 500 mm, respectively, which may be related to the inclination of the seam (N-E). It was the direction of water outflow from the backfill, and it may mainly result from the reactivation of the network of old excavations, which occur mainly in the eastern part, Figs. 7 and 9.
- The applied width of the coal pillars gave positive results, although the a posteriori values of exploitation coefficients were almost 2÷3 times higher than those determined by a priori by means of numerical modelling, and the deformations doubled.
- There was (unforeseen) a large impact of the operation of individual gallery excavations on surface deformations, bored at an average depth of 270 m. The exploitation of individual galleries in the north-eastern part resulted in an increase in depression to 260 mm, and in the western part to 100 mm. The reason for this increase was the reactivation of old galleries, located on the 270 m mining level, seam 507, as well as the low efficiency of decommissioning of old and new galleries.

New experiences concern the impact of partial mining on surface deformations and the deformation of coal pillars.

Assuming the output data of the analysed operation, the height of mining excavations g = 3.8 m, the width of excavations s = 5.6 m and the depth of exploitation H = 300 m. The width of the coal pillar determined on the basis of a nomogram presented in Fig. 2 (she, 1975) should be about 15 m, so it was analogous to the numerically determined width. Despite this, the surface deformations were twice as large as those measured later.

The comparative analysis also used an empirical formula for the factor of safe coal pillar in the form (Whittaker and Smith, 1987) and (Whittaker and Reddish, 1989)

$$Factor\ of\ safety\ against\ coal\ pillar\ failure = \frac{7180\left(\frac{p^{0\times 46}}{g^{0\times 66}}\right)}{23H\left(\frac{w+p}{p}\right)^2}$$

where:

p – dimension of the side of a square coal pillar,
w – width of the excavation,
g – thickness of the exploited seam,
H – depth of exploitation.

Assuming p = 4.0 and 14 m, excavation width 5.6 m and depth H= 300 m, the factor of safe coal pillar determined from formula (1) is 0.14 and 0.74. According to British research, for the factor ≥ 1.0, which is the limit value, the pillar is safe for both surface and mining excavations. It should be noted that Salamon and British researchers determined the safety factor for smaller exploitation depths of 50-100 m. Polish tests show that for 4.0 m wide coal pillars, the determined exploitation factor was a = 0.4, which was confirmed by tests from exploitation in another field (Polanin, Kowalski, Walentek, 2019). For coal pillars with a width of 12 m, which can be considered safe for the surface and stability of mining excavations, the exploitation factor was 0.2, and on the surface, there were deformations corresponding to the 1st category of the mining area.

Therefore, the methods for determining safe coal pillars for operation by belts or galleries may be different, but they both must take into account the specificity of geological and mining conditions. The quoted nomograms and patterns from the world hard coal mining referred to the rock mass at smaller depths (generally 200 m) and, above all, not affected by previous mining. In the analysed example, the rock mass was affected by old galleries in the former decommissioned protective pillar for the shaft and full exploitation around the pillar. The basis should be the results of surface deformation measurements, which are an objective test of the method or theory used.

Conclusion

1. It has been shown that it is possible to exploit the remains of hard coal seams in mines intended for decommissioning by operation by galleries while leaving coal pillars and by the liquidation of excavations with backfill from waste (dust) from power plants, with an average utilisation rate of 30%. It resulted from strict requirements for surface protection, limitation of deformation to the corresponding 1st category of the mining area. This is the basic and new experience in exploitation by galleries of the remains of seams.
2. The value of the exploitation factor in the rock mass was 0.21, and parameter tgβ = 1.0. The mining was based on the group of galleries with a width of 5.6 m while maintaining pillars between galleries amounting to an average of 12 m. Operation with single galleries may cause that the value of the exploitation coefficient ranged between 0.05 and 0.25 (!). It has been shown that depression may occur on the surface due to the exploitation of individual galleries in the rock mass affected by earlier excavations at an average depth of 300 m.
3. The lower efficiency of operation based on galleries in the analysed example compared to earlier partial exploitation with backfilling in Poland, or contemporary American and Chinese experience results from geological and mining conditions, where mining operation was carried out in rock mass not disturbed by previous exploitation.
4. The basis for the use of computational methods and theories or empirical formulas should be the results of measurements, which objectively evaluate and assess applied method or theory.

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