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The application of Knothe's theory for the planning of mining exploitation under the threat of discontinuous deformation of the surface and for the prediction of ground surface movements with rising water levels in the post-mining phase

Introduction

The rapid expansion of the European coal mining industry since the early days of the industrial revolution at the end of the 19th and beginning of the 20th century, and following the two World Wars, combined with a growth in population density in the coalfield areas, resulted in increasingly frequent incidents of mining-induced damage to surface buildings

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and local infrastructure. This trend led indirectly to the development of specific subsidence forecasting techniques.

Those methods have been developed World Wide for predicting mining-induced surface and rock mass movements, and these have been the subject of a number of reports in the technical literature. Some of the methods devised during this period are worthy of mention, namely those developed by Schmitz in 1923 and Keinhorst in 1925 (Keinhorst 1925), Bals in 1932 (Bals 1932), Beyer in 1945 (Beyer 1945), Knothe in 1953 (Knothe 1957, 1953) and Ruhrkohle (Ehrhardt and Sauer 1961). Most of these techniques were aimed at predicting the expected degree of subsidence in level formations. The only exception being the Knothe's and the Ruhrkohle methods, which were capable of forecasting all mining-related ground movements, i.e. subsidence, tilt, curvature, horizontal displacement and relative horizontal change in length. Knothe assumed that for an infinitesimal quantity of mineral extraction the subsidence trough would be qualitatively identical to the Gaussian function (Jiang et al. 2020; Sroka et al. 2018), while the solution proposed by Budryk (Budryk 1953) made it possible to predict horizontal ground movement . The solutions put forward by Knothe and Budryk are still widely used around the world today (Karmis et al. 1990; Lian et al. 2011; Luo and Cheng 2009).

1. Pre-calculation of mining-induced ground movements and subsidence limitation in the mine plan

Coal was the European most important fuel for many years (Janson et al. 2020). This meant that coal supplies were a matter of strategic public concern, with mining projects taking precedence over private interests (Kirby 1977). The key message during this period in European history was 'Bear up and take the money', which in practice meant that property owners affected by mining subsidence could do little to change things as they stood, but would be able to claim compensation for damage sometime later. It was therefore hardly surprising that the impact of mining operations on the ground surface was given little or no attention during the approval procedure (Król-Korczak and Brzychczy 2019).

The location of the deposits was the key factor in the planning of mine layout, and attention was given to surface protection measures only when structures of special importance were concerned. This usually resulted in the partial or complete abandonment of mining in the area in question. Determining the extent of the ground movements and the location of the main influence zones was deemed to be sufficient as regards predicting the changes likely to take place at the surface (Bischoff et al. 2010). As working depths increased and the associated influence zones became ever larger, it eventually became impossible to carry out mining operations without exerting some kind of effect on the surface structures (Oei et al. 2020; Walentek 2019).

This state of affairs existed for years until March 16, 1989, when the Federal Administrative Court's brought a fundamental change to the approach – 'Moers-Kapellen ruling'.

Henceforth, Ruhrkohle AG has to focus not on predictive calculations, but on subsidence mitigation in mine planning.

Mine planning for subsidence mitigation must be carried out in such a way that the predicted ground movement elements do not exceed the characteristic thresholds for the sensitivity of individual objects or groups of objects to mining effects (Kowalski et al. 2021; Zhu et al. 2018).

Subsidence limitation in mine planning requires at least three components (Luo et al. 2021; Marcak and Pilecki 2019), namely:

- a proven and functioning mathematical model (dynamic pre-calculation method);
- knowledge of the relevant characteristic values as based on *in situ* measurements or previous experience;
- real stress parameters and limits for surface objects needing protection, taking account of safety-related aspects, commercial considerations, and public interest factors.

Provided that the three aforementioned elements are known, and by factoring in the existing infrastructure (surface and underground), the following planning criteria can then be determined (Sroka et al. 2015):

- the extraction method (longwall or partial extraction with caving or pneumatic stowing);
- the working face layout in space and time (face geometry, thickness, rate of face advance, time gap to the next extraction panel);
- type and scope of monitoring and safety measures required for target objects (buildings and structures), both during and after the extraction phase;
- the scope of measurements for object monitoring and parameter identification under the Ruhrkohle method.

Here it is self-evident that a combination of the aforementioned elements may result in various planning options, with the primary decision-making criterion generally being that of cost.

As a part of this research work a series of algorithms was developed and implemented for various tasks, namely:

- determination of the characteristic values for the chronology of the face extraction sequence (Sroka 1993);
- definition of the working fields boundaries (with reference to surface objects as well as to mine roadways and shafts) (Grün 1995; Pohl 2001);
- planning of the extraction sequence in and around existing zones of discontinuity (Grün 1998);
- prediction of the mining-induced earth tremors (Fritschen 2001; Schmidt-Schleicher 1997);
- evaluation of the sensitivity of surface objects (Grün et al. 2003).

Several of these important research projects are listed in Table 1.

Table 2 presents the schemes that were outlined at the time for optimized subsidence mitigation in mine planning and the development of mining dynamics from a subsidence engineering point of view.

Table 1. Research projects on mining dynamics in the coal industry

Tabela 1. Projekty badawcze dotyczące dynamiki wydobycia w przemyśle węglowym

RAG projects	ECSC project 'Reduction of mining-induced environmental impacts'
Determining the optimum rate of face advance from a mining subsidence perspective (Apr 1995–Dec 1996)	Mining-induced earth movements (Nov 1998–Oct 2001)
In situ investigations of the mining dynamics of a face swinging operation from a mining subsidence viewpoint (Nov 1996–Jun 1999)	Classification of structures according to sensitivity and possible options for protecting them from the impact of mining operations (Nov 1998–Oct 2001)
Impact of underground mining on the development of earth tremors (Jul 1996–Jun 1999)	

Table 2. Mining dynamics from a subsidence perspective

Tabela 2. Dynamika wydobycia z perspektywy osiadania

Mining dynamics in terms of surface subsidence	
Elements of mining dynamics	◆ rate of advance ◆ exploitation chronology (standard operation – 5-day week – continuous)
Basis for determining the key elements	◆ sensitivity of the surface objects ◆ planned mining features ◆ layout; face length; depth; thickness ◆ excavation ratio ◆ measurements for determining the parameters involved ◆ calculation system (modified Ruhrkohle method)
Core statements on mining dynamics	◆ subsidence-limiting dynamic measures ◆ extending the timeframe of the mining impact (adjustment of the rate of face advance) ◆ levelling the mining impact (continuous extraction) ◆ adaptation of the face geometry (broader faces; multi-face systems are more favourable)

These developments exert an influence on the ongoing evolution of the Ruhrkohle method. The actual position of the seam within the body of rock (irregular bedding, changeable seam thickness), the excavation ratio, the anisotropy of the strata, and the delay characteristics of the overlying rock have all been incorporated into the forecasting process.

The way in which this has been applied to the planning process in practical terms is illustrated below using two examples from 1992 and 1997. The first example concerns coal extraction in the Mausegatt seam, based on four longwall faces operating simultaneously beneath the Kapellen district of the German town of Moers. The second example involves the extraction of coal panel 479 in the Johann seam lying directly in the fissure zone of Recklinghausen-North.

1.1. Extraction of the Mausegatt seam beneath the district of Moers-Kapellen – example 1

In 1992, despite some major subsidence events previously caused by an unstable ground reaction to mining operations, Niederberg colliery took the decision to start planning for the extraction of the Mausegatt seam beneath the Kapellen district in Moers. The average working thickness for the Mausegatt seam, which was about 750 m below ground level, was determined at around 0.8 m. To prevent the emergence of new linear type discontinuous deformation, and to avoid re-activating those already present, the Kapellen district would also have to be completely supported.

Basing the extraction around four working panels was planned. However, the new production district included two problem areas for which solutions had to be found as a part of the planning phase. The first task involved the layout geometry of the area lying to the north-east of the Kapellen district. Tectonic conditions induced by the Neukirchen fault meant that a pillar had to be left in place between panels 651 and 652, for which a width of 60–80 m was specified (average 70 m). The pillar would lie directly below the discontinuity zone close to the pre-existing zones of discontinuity, and would run almost parallel to the ribs of the proposed working panels (Figure 1).

Figure 1 presents a schematic view of the workings that were planned for the Mausegatt seam. This west-to-east profile runs both across the direction of face advance and across the direction of the zones of discontinuity on the surface.

Here the width of the pillar and the length of the coal face for panel 652 were to be calculated so that there would be no subsidence abnormalities (surface bumps) on the discontinuity zone and no distortion acting at right angles to the direction of the existing zones of discontinuity.

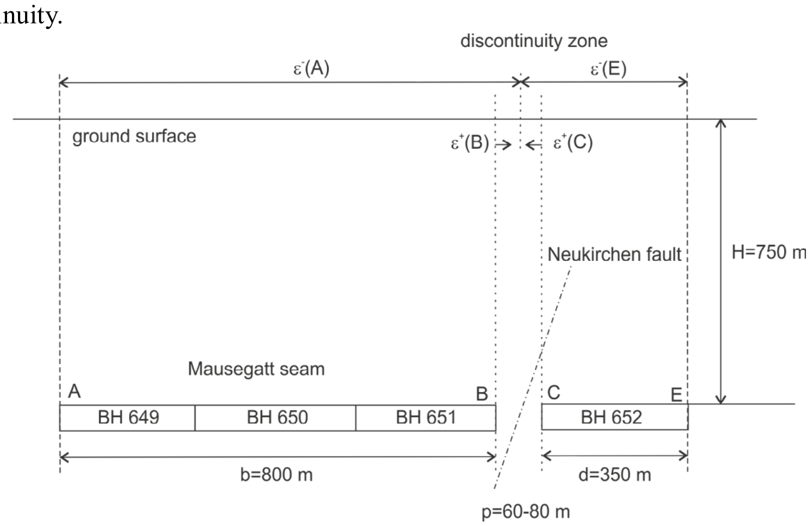

Fig. 1. Scheme of West-East section through the planned panels in the Mausegatt seam

Rys. 1. Schemat przekroju zachód–wschód przez planowane ściany w pokładzie Mausegatt

Mining dynamics also played a particular role in the proposed configuration. Irrespective of how this factor was defined, it always had to be analyzed both qualitatively and quantitatively in terms of the rate of advance and the parameters for the chronology of attack. It was self-evident that the dynamics of an individual production unit could not be compared with those of three or four parallel working faces in simultaneous operation. This was the second task.

The four edges marked A, B, C, and E in Figure 1 impact those areas of the surface that lie above the pillar. The objective was to design pillar *p* and face length *d* of panel 652 in such a way that the summary deformation (i.e. the horizontal change in length) at point 0, which lies at the ground surface above the pillar, would be less than or equal to zero (≤ 0 mm/m), i.e. there would be no possibility of distortion due to mining.

The magnitude of the individual edge effects at point 0 depends on their normalized distance. The latter is defined as a quotient of the absolute distance and the critical area radius R ($R = H \cdot cot\gamma$). Due to the large normalized width B of the western panels 649, 650 and 651 ($B = b/R > 1$), it was assumed in the calculations that the squeezing effect exerted by edge A on point 0 was practically zero. The distortion and deformation ε^+ from edges B and C must accordingly be offset by pressure ε^- coming from edge E.

The distortion exerted by edges B and C at point 0 is approximately equal and amounts to

$$\varepsilon_B^+ = \varepsilon_c^+ = \varepsilon^+\left(0.5P\right) \tag{1}$$

where P is the normalized pillar width ($P = p/R$).

The squeeze exerted by edge E amounts to

$$\varepsilon_E^- = \varepsilon^-\left(D + 0.5P\right) \tag{2}$$

where D is the normalized face length of panel 652.

This produces the following equation:

$$2\varepsilon^+ (0.5P) + \varepsilon^- (D + 0.5P) \leq 0 \tag{3}$$

As this equation indicates, the normalised pillar width P and the normalised face length D of panel 652 are highly dependent on each other.

The interdependency between the absolute pillar width (in the range between 60 and 100 m) and the permitted face length of panel 652 for the three fixed limit angle values (50, 55, and 60 gons), as calculated according to the Ruhrkohle method, is shown in Figure 2.

An analysis of measured levels of subsidence resulting from previous workings in the Geitling 1 and Geitling 2 seams showed that the specific limit angle value for the colliery was about 55 gon (see Sroka 1993). The calculation results presented in figure 2 show that the colliery's planned face length of 350 m satisfies the equation (3) when the limit angle is

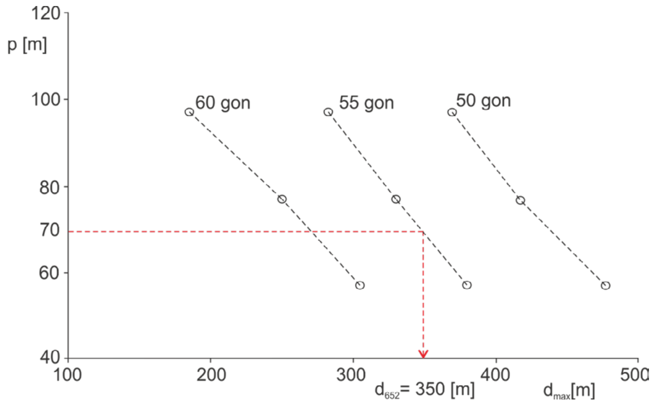

Fig. 2. Interdependency between pillar width and face length in panel 652 as a function of the limit angle

Rys. 2. Zależność między szerokością filara a długością ściany 652 jako funkcja kąta granicznego

55 gon and the pillar width is up to about 73 m, and this, therefore, prevents any distortionary impact on the ridgeway area. The length measurements carried out during the winning phase gave no indication at any time of distortion of this kind. Following the extraction of panels 649, 650, 651, and 652 in the Mausegatt seam, no new or reactivated zones of discontinuity were observed in the supported area.

With a view to adapting the dynamic impact of the underground operations to the sensitivity of surface objects to mining-induced influences, the maximum permissible rate of face advance was then determined using the knowledge available at the time. This was based on literature research, individual solutions, and *in situ* observations of subsidence movements and horizontal changes in direction during the extraction of the Geitling seam.

A solution for establishing the maximum permitted rate of advance was then formulated on the basis of the theoretical relationship between the maximum rate of settlement and the maximum subsidence slope or tilt:

$$v_{\max} = \frac{\dot{s}_{Gr}}{T_{\max}} = \sqrt{\frac{\pi}{k}} \cdot \frac{\dot{s}_{Gr}}{s_{\max}} \cdot R \tag{4}$$

k – is a constant in the Ruhrkohle method ($k = -\ln 0.01$);
$s_{\max}$ – is the maximum subsidence value (for the critical area $s_{\max} = a \cdot M$);
R – is the critical area radius;
$\dot{s}_{Gr}$ – is a limit value characterising the sensitivity of structural objects to mining-induced effects.

Taking the existing buildings and infrastructure in the Kapellen district and the previous impact of underground mining operations into account, a limit value for the rate of ground settlement of $\dot{s}_{Gr}$ = 6.0 mm/Tag (6.0 mm/day) was laid down as a means of determining the maximum permitted rate of advance of panels 649, 650, 651 and 652 in the Mausegatt seam.

Allowing for the characteristic limit angle value of γ = 55 gon for Niederberg colliery, the maximum rate of face advance was then established as

$$v_{\max} = 4.5 \text{ m/day}$$

On the basis of measurements taken during the extraction of the Geitling 1 seam, it was found that operational stoppages to the mining operations (e.g. weekend rest days) tended to interrupt the continuity of the sequence of movement and deformation, particularly in and around the zones of discontinuity.

The highly negative impact that this was having on surface buildings and structures led to the recommendation that coal mining should be undertaken on a continuous basis (7 days a week) at a maximum rate of advance of 4.5 m/day. These new working measures achieved their objective in that they minimized the damaging impact that mining operations were having at the surface.

The mine layout diagram below shows the synchronized extraction sequence used for the four parallel production faces. The example described here is still referred to as the 'Niederberg quadrology' (Figure 3).

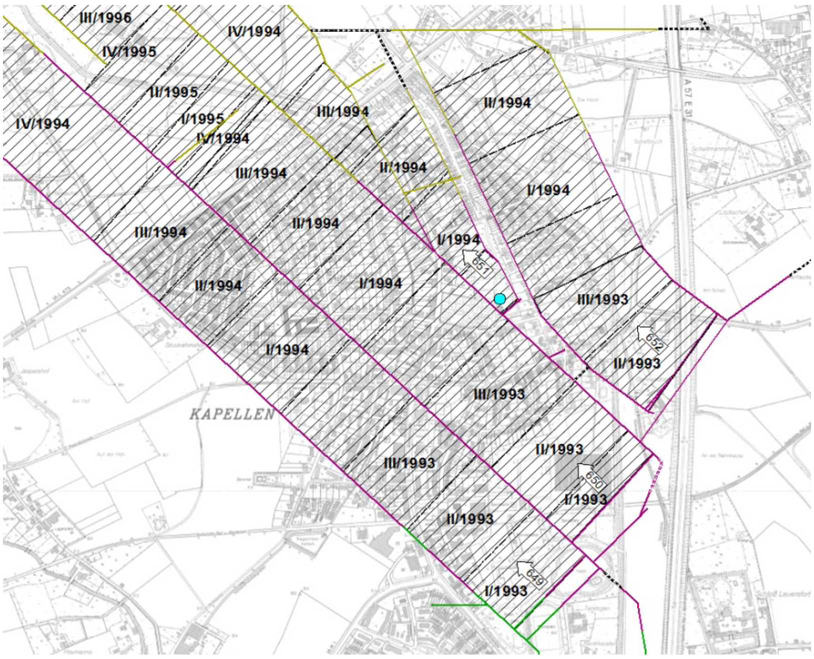

Fig. 3. Layout and extraction status of the Niederberg quadrology

Rys. 3. Układ i stan wydobycia czterech ścian w kopalni Niederberg

Based on the measurements and surface observations carried out during the operation of the Geitling 1 seam, it was clearly established that weekend stoppages were causing a cyclical disruption to the sequence of movement and pattern of deformation of surface objects and to the existing zones of discontinuity, and that this generally had a negative impact on the surface structures in question. For this reason, it was advised that the winning routine should be switched to continuous coal mining with a maximum rate of advance of 4.5 m/day.

1.2. The extraction of coal panel 479 in the Johann seam lying directly in the fissure zone of Recklinghausen-North – example 2

The BAB A43/B225 motorway bridge structure is located at the northern edge of the B1 is a part of the former Blumenthal/Haard colliery. The bridge is subject to the influence of the Recklinghausen-North fissure zone, which is geogenic in origin. The mining operations in the Wilhelm, Wasserfall, Sonnenschein, and Johann seams, which commenced prior to the extraction of panel 479 in the Johann seam (Sroka and Grün 1996), resulted in discontinuous ground movements in the form of gaps opening up in the fracture zone (Figure 4).

Measurements taken in the zone of cleavage during the period from April 1987 to December 1995 showed that a cumulative gap of about 200 mm had opened up (Figure 4).

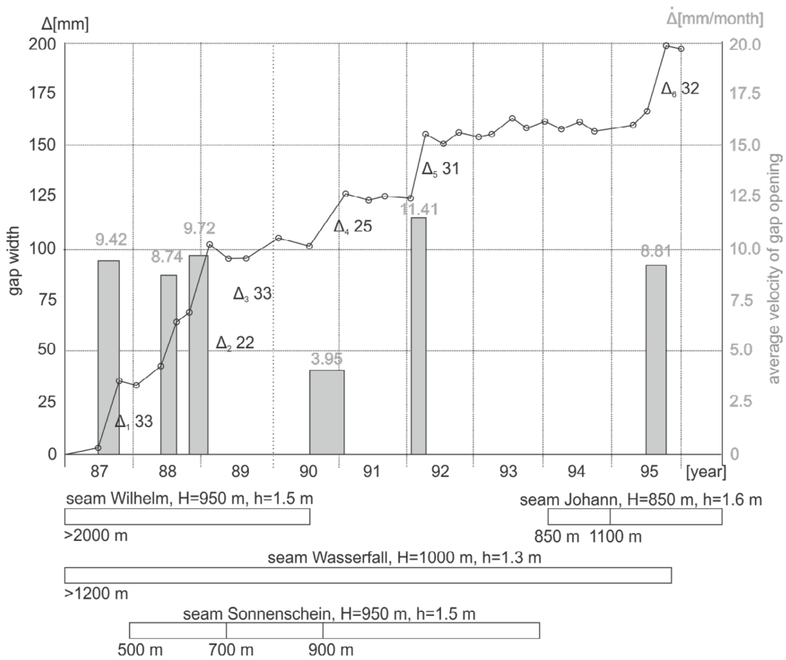

Fig. 4. Measurement line along Dorstener Street at point 24–25

Rys. 4. Linia pomiarowa wzdłuż ulicy Dorstener w punkcie 24–25

An analysis of the time-line of the development of this gap showed that the cumulative gap had been created by six individual events (Δ_{1-6}) with openings of between 22 and 33 mm (average 30 mm).

It was suspected that the extraction of panel 479, which was planned for early 1997, would cause even more gaps to open up in the fissure zone and could thereby pose a threat to the bridge structure and to the flow of the motorway traffic.

As the working geometry and direction of advance for the planned panel 479 had already been fixed, the only possible option for minimizing subsidence damage was to limit the rate of advance, this being based on a permissible gap opening rate that was selected in accordance with safety criteria. This entailed:

- extending the impact of coal mining operations by limiting the rate of face advance;
- levelling the impact by maintaining a continuous and constant rate of advance over the entire week.

It was reasonable to expect that even these measures – limiting the rate of advance and introducing a continuous mining regime – would ultimately not prevent the further opening of gaps in the fissure zone. However, they would help to reduce the rate at which the gaps were opening, and to level out the entire process of movement during the coal winning phase. This was crucial for the successful application of strata injection measures aimed at stabilizing the bedrock during this critical period.

At this time, gaps were opening at an average rate of between 8.7 and 11.4 mm/month. In view of the measurement interval of about 2.5 to 3.6 months and the likelihood of a discontinuous pattern of movement over time, it could safely be assumed that the actual maximum rate at which gaps were opening was in fact much higher.

The experience acquired by the colliery and the various firms involved indicated that the measured rate of gap development could be managed by employing appropriate technical measures in the subsoil zone and around the motorway bridge.

The ground stabilization measures carried out since 1980, along with the structural reinforcement work that was occasionally needed at the bridge, have proved adequate over the years. As the permitted rate of advance could only be determined by specifying a technically manageable gap opening rate, those involved – including the firm responsible for carrying out the injection work for ground stabilization – all agreed on a limit value of $\dot{\Delta}_{Gr}$ = 7.5 mm/month.

The Ruhrkohle method was used as a basis for the mathematical model that was developed to calculate the maximum horizontal opening of the fissure zone and the maximum gap development rate.

For a point at a distance x from the lateral edge (Figure 5) the average value of the horizontal displacement under undisturbed strata conditions can be calculated using the following equation:

$$\bar{u}(x) = u_{\max}\left[\exp\left(-k\frac{x^2}{R^2}\right) - \exp\left(-k\frac{(x+d)^2}{R^2}\right)\right] \tag{5}$$

u_{max} – is the maximum horizontal displacement for the critical area;
k – is a constant for the Ruhrkohle method (k = –ln 0.01);
R – is the critical area radius.

The geometric situation of the production faces planned for panel 479 is presented schematically in Figure 5.

For the condition

$$x + d > R$$

the following is obtained:

$$\bar{u}(x) \approx u_{max} \exp\left(-k\frac{x^2}{R^2}\right) \tag{6}$$

The findings obtained from an analysis of the *in situ* measurements in the area of the Recklinghausen-North fissure zone indicate that only a small fraction of the mining-induced impact is transferred through the fissure zone, which means that this zone has a shielding effect.

This concurs with the experience that the coal industry has acquired on the left bank of the Lower Rhine (see for example Grün 1995). The transfer coefficient η derived from these measurements has a maximum value of between 0.10 and 0.15.

Under the assumption of the screening effect of the fissure zone and a continuous winning regime at a constant rate of advance, the following solutions are obtained for deter-

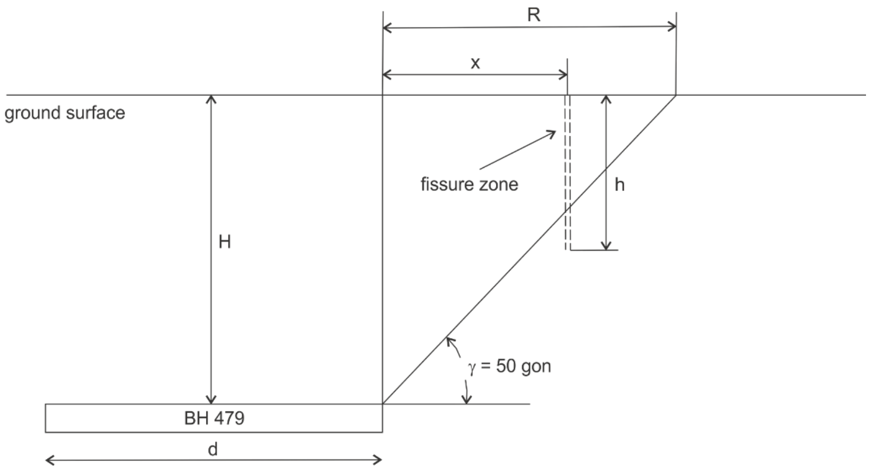

Fig. 5. Summary presentation of situation relating to example No. 2

Rys. 5. Podsumowanie sytuacji odnoszącej się do przykładu nr 2 mining the maximum mining-induced gap development Δ and the maximum opening rate $\dot{\Delta}$.

$$\Delta_{\max}(x) = 2 \cdot (1-\eta) \cdot \bar{u}(x) \tag{7}$$

$$\dot{\Delta}_{\max}(x) = \Delta_{\max}(x) \cdot \sqrt{\frac{k}{\pi}} \cdot \frac{v_{pl}}{R} \tag{8}$$

η – is the transfer coefficient;
v_{pl} – is the planned rate of advance.

The calculation scheme for the quantities $\Delta_{\max}$ and $\dot{\Delta}_{\max}$ is shown in Figure 5 and Table 3 along with the relevant face data, the characteristic values of the Ruhrkohle method, the data for the fissure zone and the calculation formula.

Predictions based on the colliery's planned rate of advance of v_{pl} = 5.68 m/day and a transfer coefficient value of $\lambda = 0$ (worst case scenario) gave a maximum gap development rate of around 10.1 mm/month and a maximum gap opening of 40 mm.

This meant that the anticipated values were above the 7.5 mm/month threshold that had been laid down in accordance with the safety criteria. A correction therefore had to be made to the rate of advance, and as a result the maximum face advance was set at around 4.2 m/day in accordance with the following formula (9):

Table 3. Face data of BH 479, the characteristic values of the Ruhrkohle method, the data for the fissure zone and the calculation results

Tabela 3. Dane ściany BH 479, wartości charakterystyczne metody Ruhrkohle, dane dla strefy występowania szczeliny i wyniki obliczeń

Face data of BH 479	Characteristic values of the Ruhrkohle method	Data for the fissure zone	Calculation results (based on planning)	Calculation results (based on the correction)
Depth H = 830 m	Subsidence factor a = 0.9	Gap length l > 15 km	Gap opening $\Delta_{\max}$ = 40 mm	
Thickness M = 1.65 m	Boundary angle γ = 50 gon	Gap depth h > 150 m	Gap development rate $\dot{\Delta}_{\max}$ = 10.1 mm/mo.	$\dot{\Delta}_{Gr}$ = 7.5 mm/mo.
Length d = 256 m		Distance from the wall x = 712 m		
Run B = 1500 m		Conductivity coefficient η = 0		
Planned rate of advance v_{pl} = 5.68				$v_{\max}$ = 4.2 m/day

$$v_{\max}(x) = v_{pl} \cdot \frac{\dot{\Delta}_{Gr}}{\dot{\Delta}_{\max}(x)} = \sqrt{\frac{k}{\pi}} \cdot \frac{\dot{\Delta}_{Gr}}{\dot{\Delta}_{\max}(x)} \cdot R \tag{9}$$

In view of the importance of the structure to be protected, a high-traffic motorway bridge (BAB A43/L225), the management of the then Ruhrkohle Bergbau AG took the decision to implement the measures recommended in the Internal Opinion. The face advance rate and the continuity of the extraction regime were subsequently placed under close supervision based on regular on-face surveys combined with permanent monitoring of the coal conveying equipment.

1.3. Projection of uplift due to rising mine water levels – case study

The scientific investigations carried out during the coal winning phase focused on the problems associated with predicting the mining-induced ground movements and on mine planning methods aimed at minimizing surface subsidence. With the end of the German coal mining industry insight, these investigations then switched their focus increasingly to the ground movements that would be initiated by rising mine water levels.

The suspension of water pumping operations after a colliery has closed down will lead to a large-scale rise in mine water levels, and this can, in turn, result in extensive areas of measurable surface uplift, as has been borne out by observations and experiences at national and international level. The damage caused by rising mine water at the Sophia Jacoba colliery in the Erkelenz coalfield district led to an intensification of scientific efforts aimed at developing an effective method for predicting ground movements due to rising mine water levels. This topic has been the focus of a series of research investigations and projects that the current RAG company has carried out over the past 15 years.

The question of potential damage relevance here is very closely linked to that of the predictability of the ground uplift and horizontal movement components that can be expected as a result of an increase in mine water levels.

Sroka and Preusse, working within the framework of a RAG-funded research project, developed a mathematical model whose formal mathematical structure is identical to the geometrically integral geodetic method of subsidence projection (Dudek et al. 2020; Dudek and Tajduś 2021; Müller and Preusse 2018). This method is based on the assumption that a rise in mine water levels leads to an increase in pore pressure in the rock zone that has been fractured by mining operations (Preusse and Sroka 2015; Sroka 2005; Sroka and Preusse 2009). This, in turn, causes that zone to extend outwards in a vertical direction.

It was decided that the horizontal expansion of the fractured rock zone is identical to the geometry of the extracted area of the coal seam. The vertical expansion of this area is usually limited to between three and four times that of the worked seam thickness.

The method developed by Sroka and Preusse also means that even in multi-seam mining systems it is possible to predict the uplift that can be expected as a result of rising water levels.

In this case, the parameters a (subsidence coefficient) and γ (limit angle), which are needed in order to calculate the mining-induced ground movement, have to be replaced with the parameters a_w (coefficient of lift) and γ_w, which are specific to the rise in the mine water level. The lift factors are calculated on an individual seam basis as a function of the mine water level and the depth of the workings that are affected by the rising water.

$$a_w\left(z_w, z_{Fl}, t\right) = d_m \cdot \lambda \cdot \Delta p\left(z_w, z_{Fl}, t\right) = d_m \cdot \lambda \cdot \left(z_w\left(t\right) - z_{Fl}\right) \cdot \delta_w \tag{10}$$

d_m – is the coefficient of expansion of the rock zone fractured by mining operations;
λ – is the relative thickness of the fractured rock zone in comparison with the worked thickness ($\lambda = 3 – 4$);
$\Delta p(t)$ – is the increase in pore pressure in the fractured rock zone due to the rise in the mine water level at time t;
$z_w(t)$ – is the height of the mine water level time t;
z_{Fl} – is the height of the flooded working zone;
δ_w – is the water density.

The mathematical upheaval model was tested with reference to the uplift due to rising mine water levels measured at Königsborn colliery (Preusse and Sroka 2015).

Between 1996 and 2012 the mine water rose from a depth of 940 m to around 100 m below ground surface. Periodic level measurements and geometric data taken from all working areas in some 18 seams were used for parameter identification with the model tests, i.e. to establish the coefficient of expansion d_m and the limit angle γ_w.

It should be noted that the expansion coefficient d_m only applies in conjunction with the assumption made in respect of the relative height of the fractured rock zone λ. As the two values d_m and λ have a multiplicative effect, any change in the quantity λ will automatically mean a correction to the coefficient of expansion d_m.

The assumed value of λ is also often uncertain and subject to dispute. Sroka and Preusse have therefore proposed that the product of these two coefficients be viewed together as an integral expansion factor. The parameter identification for the upheavals in the area of the Königsborn colliery that were measured during the period up to 2012 yielded the following results: $d_m \cdot \lambda = 1.092 \cdot 10^{-2}$ m^2/MN and $\gamma_w = 12$ gon.

For the assumption $\lambda = 3$, i.e. the height of the fractured rock zone is three times the worked thickness, this means that the following relationship is obtained: $d_m = 0.364 \cdot 10^{-2}$ m^2/MN.

Figure 6 shows the distribution of uplift along a west-to-east profile for three selected final gauge levels as calculated with the identified parameter values of the mathematical upheaval model incorporating all worked-out areas below ground.

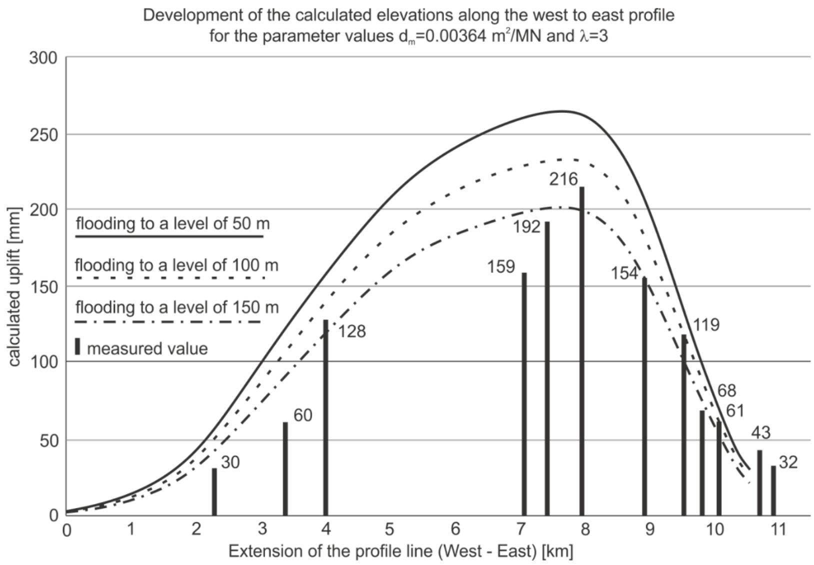

Fig. 6. Development of calculated uplift along a west-to-east profile

Rys. 6. Rozwój obliczonego wypiętrzenia wzdłuż profilu z zachodu na wschód

A comparison of the calculated distribution with the measured uplift values (as at 2012) shows a good correlation both qualitatively and quantitatively.

Conclusions

Stochastic methods based on the theory proposed by Knothe and the development of the 'Ruhrkohle method' according to Ehrhardt and Sauer have been successfully employed for a number of decades to predict mining-induced ground movements. The possibility of forecasting both vertical and horizontal ground-shift elements provided an opportunity to optimize mining projects in terms of the anticipated ground movement. This process would require both the existing calculation models and the determination of prediction parameters using geodetic measurements.

The consideration of mining-dynamic aspects created a further step in the development of subsidence limitation in mine planning. The key here was to exercise control over the face advance rate and the continuity of the extraction regime.

Even if it is not possible to avoid ground movements completely – and hence eliminate mining subsidence affecting structural objects – when coal is being mined at deep levels beneath heavily built-up areas, the prediction methods as described above have yielded significant improvements. This is borne out by the examples provided.

Certainly ground uplift due to rising mine water levels is not a major factor in mining-related damage, yet movements of this kind also need to be predicted. As the example of the former Königsborn colliery shows, stochastic processes are well suited for predicting ground uplift, provided small adjustments are made to the model and suitable parameters applied.

This has also been confirmed by preliminary work undertaken by RAG to investigate ground uplift due to rising mine water levels in the area of the Warndt take in the Saar coalfield.

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THE APPLICATION OF KNOTHE'S THEORY FOR THE PLANNING OF MINING EXPLOITATION UNDER THE THREAT OF DISCONTINUOUS DEFORMATION OF THE SURFACE AND FOR THE PREDICTION OF GROUND SURFACE MOVEMENTS WITH RISING WATER LEVELS IN THE POST-MINING PHASE

Keywords

coal mining, mine flooding, uplift, surface movement, post-mining

Abstract

The article presents three German-located case studies based on stochastic methods founded by the theory proposed by Knothe and the development of the 'Ruhrkohle method' according to Ehrhardt and Sauer. These solutions are successfully applied to predict mining-induced ground movements. The possibility of forecasting both vertical and horizontal ground movements has been presented in the manuscript, which allowed for optimization mining projects in terms of predicted ground movements.

The first example presents the extraction of the Mausegatt seam beneath the district of Moers--Kapellen in the Niederberg mine. Considering, among others, the adaption of the dynamic impact of the underground operations to the mining-induced sensitivity of surface objects, the maximum permissible rate of the face advance has been determined.

The second example presents the extraction of coal panel 479 in the Johann seam located directly in the fissure zone of Recklinghausen-North. Also, in this case, the protection of motorway bridge structure (BAB A43/L225) to mining influences has been presented. The Ruhrkohle method was used as a basis for the mathematical model that was developed to calculate the maximum horizontal opening of the fissure zone and the maximum gap development rate.

Part of the article is dedicated to ground uplift due to rising mine water levels. Although it is not the main factor causing mining-related damage, such movements in the rock masses should also be predicted. As the example of the Königsborn mine, liquidated by flooding, shows stochastic processes are well suited for predicting ground uplift. The only condition is the introduction of minor adjustments in the model and the use of appropriate parameters.

WYKORZYSTANIE TEORII KNOTHEGO DO PLANOWANIA EKSPLOATACJI GÓRNICZEJ W WARUNKACH ZAGROŻENIA POWIERZCHNI DEFORMACJAMI NIECIĄGŁYMI ORAZ DO PROGNOZY RUCHÓW POWIERZCHNI TERENU PRZY WZROŚCIE POZIOMU WÓD KOPALNIANYCH W FAZIE POEKSPLOATACYJNEJ

Słowa kluczowe

górnictwo węglowe, zatapianie kopalni, wypiętrzenie powierzchni terenu, przemieszczenia powierzchni terenu, problemy pogórnicze

Streszczenie

Artykuł przedstawia trzy studia przypadków zlokalizowane w Niemczech, oparte na metodach stochastycznych, których podstawą jest teoria zaproponowana przez Knothego oraz rozwój „metody

Ruhrkohlego" według Ehrhardta i Sauera. Rozwiązania te są z powodzeniem stosowane do przewidywania ruchów górotworu wywołanych wydobyciem surowców. Przedstawiono możliwość prognozowania zarówno pionowych, jak i poziomych ruchów górotworu oraz zaprezentowano możliwości optymalizacji projektów górniczych pod kątem przewidywanych ruchów górotworu.

Pierwszy przykład przedstawia wydobycie pokładu Mausegatt pod okręgiem Moers-Kapellen w kopalni Niederberg. Mając na uwadze m.in. dostosowanie dynamicznego wpływu eksploatacji górniczej do wrażliwości obiektów powierzchniowych na wpływy górnicze, określono maksymalne dopuszczalne tempo posuwu przodka.

Drugi przykład przedstawia wydobycie ściany 479 z pokładu Johanna leżącego bezpośrednio w strefie nieciągłości Recklinghausen-North i zastosowane zabezpieczenie konstrukcji mostowej autostrady (BAB A43/L225). Metoda Ruhrkohlego została wykorzystana w tym przypadku jako podstawa do modelu matematycznego, który został opracowany do obliczenia maksymalnego poziomego otwarcia strefy nieciągłości i maksymalnego tempa rozwoju szczeliny.

Część artykułu poświęcona jest zjawisku wypiętrzania w wyniku podnoszenia się poziomu wód kopalnianych. Pomimo tego, że nie jest to główny czynnik powodujący szkody związane z górnictwem, jednak tego rodzaju ruchy również należy prognozować. Jak pokazuje przykład dawnej kopalni Königsborn, procesy stochastyczne dobrze nadają się do przewidywania wypiętrzenia gruntu, pod warunkiem wprowadzenia niewielkich korekt w modelu i zastosowania odpowiednich parametrów.