Archives of Environmental Protection PL ISSN 2083-4772
Vol. 48 no. 1 pp. 100–108 DOI 10.24425/aep.2022.140549

The land surface deformation caused by the liquidation of the Anna mine by flooding

Mateusz Dudek[1]*, Krzysztof Tajduś[1], Janusz Rusek[2]

[1]Strata Mechanics Research Institute, Polish Academy of Sciences, ul. Reymonta 27, 30-059 Cracow, Poland
[2]Faculty of Mining Surveying and Environmental Engineering,
AGH University of Science and Technology, al. Mickiewicza 30, 30-059 Cracow, Poland

*Corresponding author's e-mail: dudek@imgpan.pl

Keywords: mine closure, mine flooding, land surface uplift, flooding scenarios, prediction

Abstract: The most worldwide method of liquidating underground hard coal mines is by spontaneous flooding as the result of the discontinuation of the rock mass drainage. Due to the hydrological reconstruction of the previously disturbed water system by mining operations, the movements of the rock mass with the opposite direction than subsidence appear. These movements are called rock mass uplift. This paper aims to present possible hazards related to land surface objects and the environment, which can appear during the flooding of the underground mine. The issue of proper forecasting of this phenomenon has so far been marginal in world literature. To date, only a few analytical methods have been used to predict the possible effects of surface deformation. Nowadays, the most common analytical method of forecasting surface deformation caused by the liquidation of underground workings by flooding is Sroka's method.

In this paper, the authors have presented analyses of flooding scenarios developed for a Polish mine and their impact on the land surface as well as the environment. The scenarios presented in the manuscript were selected for analysis as the most probable concerning the mine and the future plans of the mining enterprise. The process of flooding coal mines results in several risks for surface objects and underground infrastructure. This is why the uplift caused by the flooding of the mine should be predicted. The resulting uplifting movements can also, apart continuous deformation lead to the creation of much more dangerous phenomena involving discontinuous deformations.

Introduction

Recent years have brought significant changes in the perception of mining and its products (A. Tajduś & Tokarski, 2020). The resolution adopted in 2019 on limiting energy production from hard coal accelerated the process of closing hard coal mines in some countries. In Poland, this problem is raised more and more by both the public and politicians. The increase in use of renewable energy resources in Poland is crucial due to the poor performance of the Polish energy system (Mróz & Grabowska, 2021), based on the supply of high carbon content fossil fuels and its impact on the environment (Wasielewski et al., 2020; Zwierzchowski & Różycka-Wrońska, 2021). Recently, as a result of negotiations between the government and representatives of the coal industry and trade unions, the date of ending coal mining in Poland for 2049 was set. Without going into discussion, whether this term is possible due to socio-economic and environmental aspects (Kowalska, 2014; Wysocka et al., 2019), it should be noted that the process of decommissioning European mines has already started.

In Germany, at the end of 2018, the last BW Prosper-Haniel underground hard coal mine was closed. In Poland, from 2015 to 2021, five mines were closed or planned for closure (the Boże Dary mine, the Brzeszcze Wschód mine, the Mysłowice mine, the Wieczorek I mine, and the Wieczorek II mine), in the Czech Republic currently, a liquidation process is implemented on the OKD Lazy and Darkov mines, and all of the company's mines are expected to close by 2023. However, the liquidation of an underground mine, which has been operated for many years, is not an easy process and carries many risks. Currently, the most popular method of liquidation of an underground mine is its self-flooding, i.e., after appropriate preparatory works, the mine turns off the pumping systems of the mine water flowing into the workings, and its flooding occurs automatically (K. Heitfeld et al., 2003; Jakubick et al., 2002; Krzemień et al., 2016; K. Tajduś et al., 2017). In recent years, due to the increase in the number of mines being closed in Europe, extensive research has been launched on their environmental impact and determining the risk of certain hazards and how to minimize them (Dudek et al., 2020; Dudek & Tajduś, 2021; Jewartowski et al., 2015; *Management of Environmental Risks during and after Mine Closure, Contract No. RFCR-CT-2015-00004*, 2020). One of the environmental problems that should be considered during the closure of underground mines is the deformation of the land surface, often resulting in mining damage to buildings (Baglikow, 2011; M. Heitfeld et al., 2004) and a change in hydrological conditions. During the process of an underground mine flooding, the phenomenon of continuous deformation in the form of land surface uplift and possible discontinuous deformations is observed.

This phenomenon has been described in several different coal basins in Europe, for example, in Belgium (Devleeschouwer et al., 2008), France (Samsonov et al., 2013), Germany (Baglikow, 2011; John, 2021), Poland (Preuβe et al., 2013), the Netherlands (Bekendam & Pöttgens, 1995) and Spain (Álvarez et al., 2016; Caro Cuenca et al., 2013). The duration of time required to flood the goafs of a mine depends on such factors as the number of exploited longwall panels, the availability of water for infiltration and the nature of flooding, which may be uncontrolled, controlled or monitored. Underground mines are usually flooded in a controlled manner. Here, surface water presents no direct impact, so groundwater plays the main role in this process. Currently, adequate prediction of the surface deformations caused by mine liquidation activities is a particularly important issue. Researchers continue their attempts to describe the behavior of rock mass during mine liquidation. Initially, researchers used analytical methods (Fenk, 2000; Pöttgens, 1985; Sroka, 2005), but numerical methods have also found their rightful place in predicting the phenomenon of surface uplift and rock mass deformations caused by the flooding of underground structures (Dudek et al., 2020; Dudek & Tajduś, 2021; Kołodziejczyk et al., 2007; Milczarek, 2011; Wesołowski, 2012).

In this paper, the authors have presented analyses of flooding scenarios developed for a Polish mine and their impact on the land surface as well as the environment. Analyses have been performed using methods and methodology developed by authors during their participation in an international research project concerning mine liquidation by flooding (*Management of Environmental Risks during and after Mine Closure, Contract No. RFCR-CT-2015-00004*, 2020).

Methods for predicting surface uplift resulting from mine liquidation by flooding

The change in the situation of global mining and the relation with the liquidation of numerous underground coal mines caused new environmental problems, including the hazard of surface movement in the form of uplift. The issue of proper forecasting of this phenomenon has so far been marginal in international literature. To date, only a few analytical methods have been used to predict the possible effects of ground surface deformation. The Pottgens method was used for the mining regions of the Netherlands, Belgium, and France (Pöttgens, 1985). For regions of Germany, the Fenk's method (Fenk, 2000) and then finally the Sroka's method has been used (Sroka, 2005). All of them are based on an assumption that the generated land surface uplift is related to an increase in pore pressure in a zone strongly disturbed by mining extraction (caved zone). Underground mining leads to a change in the initial state of stress, as well as the generation of new networks of rock mass fractures, which are closely combined with an increase in pore fluid storage capacity. The pressure increase in the damaged zone, originating from the height of the water column, applies a load towards the overlying strata of the rock mass, propagating up to the land surface. In this manner, changes occurring in the rock mass manifest in the form of land surface uplift (Vervoort & Declercq, 2017, 2018).

Nowadays, the most common analytical method of forecasting surface deformation caused by the liquidation of underground workings by flooding is Sroka's method. It is related to the high quality of the results and very good compliance with measurements, which was proved on several experimental mines in Poland and Germany. It allows to carry out uplift calculations for multi-seam mining by applying the superposition principle, which is not possible, for example, by the Fenk method. And this confirms the superiority of this method over others.

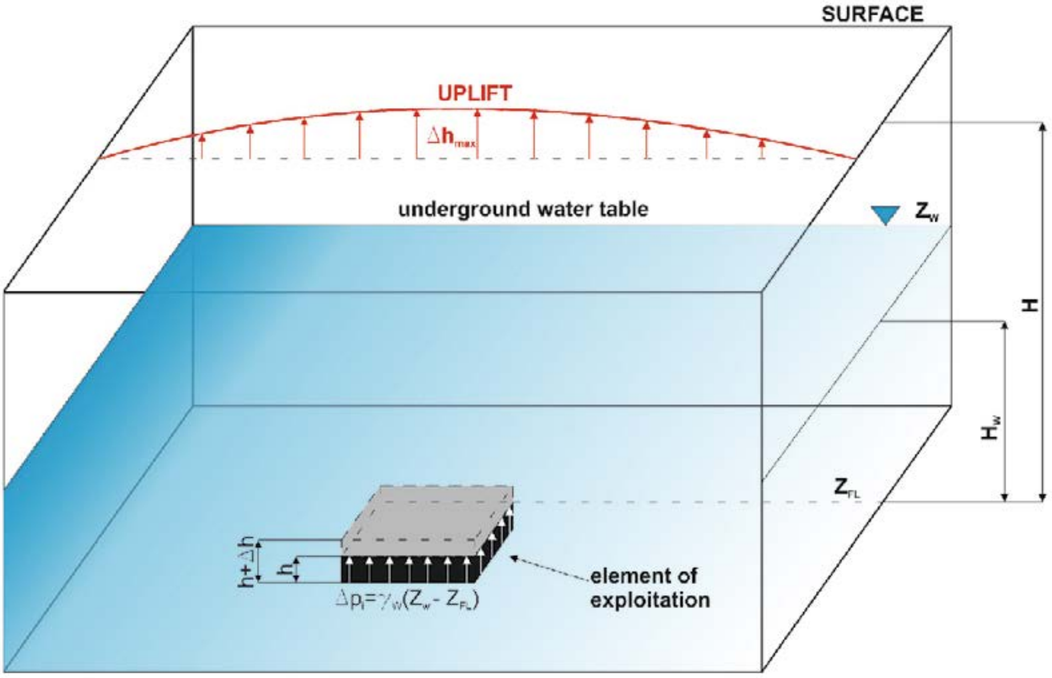

Fig. 1. Graphic representation of the mathematical model of uplifting associated with flooding proposed by Sroka (*Management of Environmental Risks during and after Mine Closure, Contract No. RFCR-CT-2015-00004*, 2020)

As presented in Figure 1, this method is based on the deposit division into finite elements. Calculations are carried out for each deposit element, taking into account the function of influence and their parameterization. The discretization of the mined-out seam surfaces into multiple elements allows for the calculation of uplift for any exploitation shapes using linear superposition. The analyses carried out during a multi-seam operation showed that the expansion coefficient dm indicated a strong dependence on the mining depth and seam thickness. A finite element describing a part of the cave-in zone due to flooding and pressure rise increases its volume, which can be described by the following formula (according to the Ruhrkohle method):

$$\Delta h(r,t) = \frac{k}{\pi} \cdot \frac{d_m \cdot \Delta p(t) \cdot \Delta V}{R_w^2} exp\left(-k\frac{r^2}{R_w^2}\right) \tag{1}$$

$$\Delta p(t) = (Z_w(t) - Z_{FI}) \cdot \rho_w$$

$$\Delta V = h \cdot \Delta x^2 = \lambda \cdot M \cdot \Delta x^2$$

$$R_w = H \cdot cot\gamma_w$$

where:

k – coefficient for the Ruhrkohle method ($k = -ln0.01 = 4.6052$),
$\Delta p(t)$ – pressure increase in disturbed zone due to the rising groundwater level,
$Z_W(t)$ – water level,
Z_{Fl} – height of the flooded element of the disturbed zone,
ρ_w – water weight,
ΔV – volume of a single element of the cave-in zone,
λ – relative thickness of the cave-in zone,
M – seam thickness,
Δx – length of the square element side,
r – horizontal distance of the calculation point from the element of the cave-in zone in the rock mass,
R_w – radius of the influence concerning liquidated mine by flooding,
H – depth of a single element,
γ_w – angle of main influence concerning liquidated mine by flooding.

For Knothe's method (Knothe, 1984), formula (1) takes the form:

$$\Delta h = \frac{d_m \cdot \Delta p \cdot \lambda \cdot M \cdot \Delta x^2}{R_w^2} exp\left(-\pi\frac{r^2}{R_w^2}\right) \tag{2}$$

In recent years, numerical methods have also been used to forecast land surface deformation caused by submerging underground mines. These experiences are mainly based on two methods:

- pressure changes, i.e., the authors of these methods applied pressure equal to the height of the water column on the modelled surface of the cave-in zone,
- changes in density, i.e., in the modelled cave-in zone, the authors changed the density of the rock mass, thus simulating rock mass flooding and obtaining an uplift of the land surface.

These solutions and their applications, possibilities, and limitations are described in more detail in (Dudek et al., 2020; Dudek & Tajduś, 2021).

Flooding scenarios developed for the Anna mine

In order to consider various probable scenarios of liquidation of an underground mine for changes in the deformation state of the rock mass and land surface, calculations were carried out for the Anna mine. By the decision of the management of the PGG mining group, the mine was to be liquidated by flooding. In this chapter, the authors presented various possible mine flooding scenarios (discussed during the MERIDA project) and the estimated rock mass deformations as a result.

The mining and geological situation of the mine

From the geological point of view, deposit Anna-1, the selected part of the former Anna mine (region R – Rydułtowy section), is located in the western part of the Upper Silesian Coal Basin (USCB), in the western and central part of Jejkowice-syncline (Fig. 2). The overburden consists of up to 120-metre-thick Holocene and Pleistocene (Quaternary) formations and Miocene (Tertiary) formations. Carboniferous formations are represented by mined Porebskie beds (coal seams of series 600) and Jaklowieckie beds (coal seams of series 700), and unmined Gruszowskie beds (coal seams of series 800).

Mining operations in the area started in the first half of the 20th century and ceased in 2017. The following seams were exploited: 615/1, 616/2, 620, 624, 626/2, 629/1, 629/2-3, 630/2, 703/1-2, 705/2-3, 708, 712/1-2 and 713/1-2 (the total thickness of the mined seams was approximately 22 meters). The Anna mine conducted underground hard coal mining operations between 1832 and 2015. The consequence of the mining operations are vast areas of goafs, however, due to a long time, the layers of mudstone and claystone in the Carboniferous cross-section were reconsolidated. Nevertheless, the areas have higher than normal water permeability.

The last stage of exploitation of deposit Anna-1 was mining longwall R-15 in seam 713/1-2, which ended in 2017. As mining operations in the area ceased, it was decided to flood the part of the deposit of the former Anna mine. It was assumed that water from the workings in the area near Chrobry I shaft would be dammed at the level of 1000 meters, and once it reaches the dam level of 7.25 meters at Chrobry I shaft, it will gravitationally flow from the parallel cross-cut at the level of 1000 meters to dewatering dip-heading R (Fig. 3).

Considered scenarios of the Anna mine flooding

To determine the degree of impact during the Anna mine flooding, risk scenarios were created and analyzed. Three scenarios have been chosen for the Anna mine, in which the occurrence possibility of ground surface and environmental hazards have been analyzed (Fig. 4). Prepared flooding scenarios are:

1. Flooding the Anna mine to the depth -801 m a.s.l;
2. Water from the Anna mine floods the Rydułtowy mine – the assumption that as a result of damage to dams separating both mines, the roadways and goafs in the Rydułtowy mine, situated in seams 700, will be flooded (flooding to the reference level of -801 m a.s.l.);
3. Flooding the Anna and Rydułtowy mines to the safe depth of -720 m a.s.l.

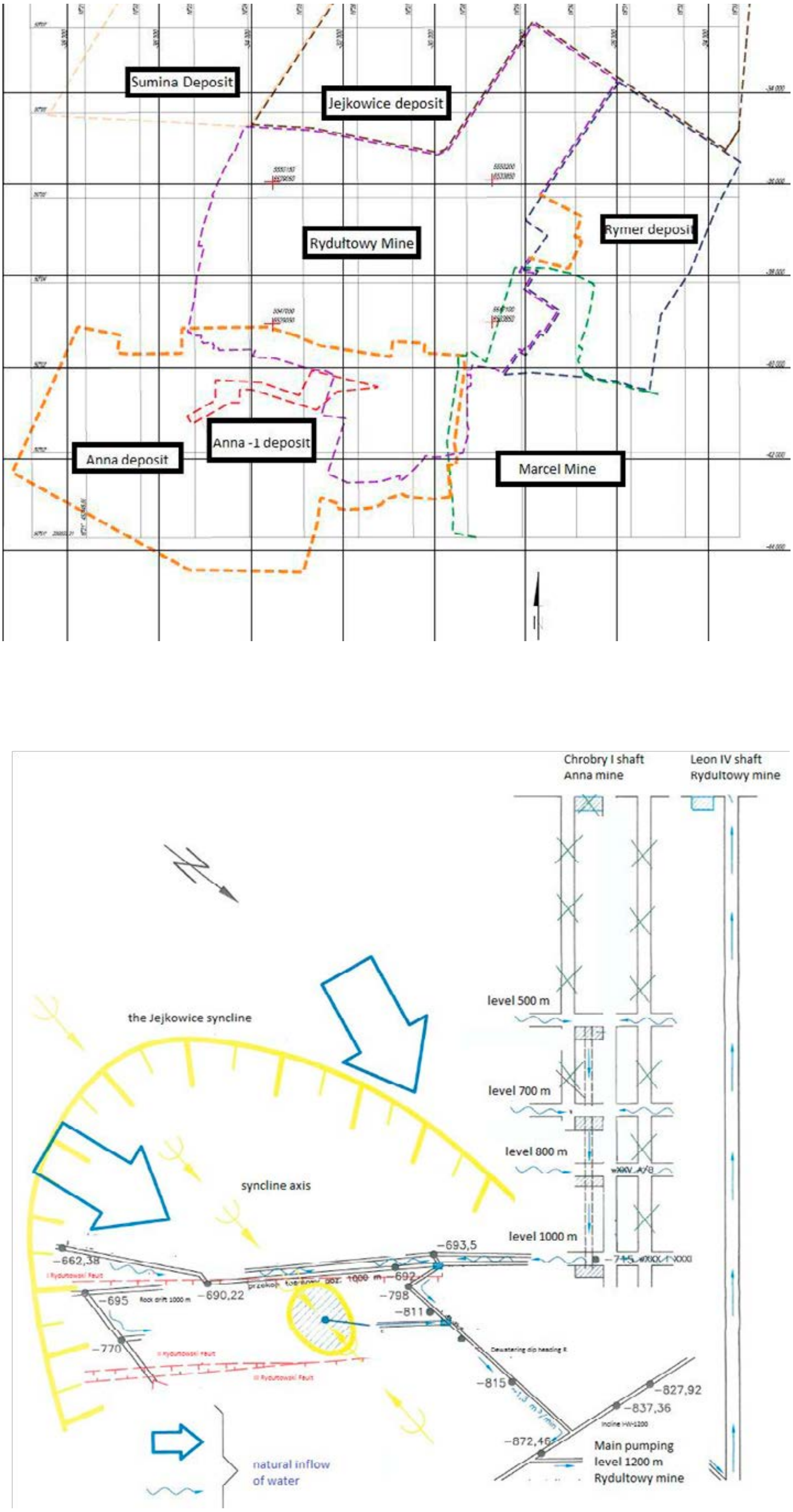

Fig. 3. *Schematics of flooding deposit Anna-1*
(*Management of Environmental Risks during and after Mine Closure, Contract No. RFCR-CT-2015-00004*, 2020)

Analyses of flooding scenarios of the Anna mine

In Poland, there are now a few areas where measurements have been taken of known ground surface deformations above mines that have been closed by flooding. A few of them include the area of the Wałbrzych coal basin, where the performed measurements have shown some changes in vertical displacements (Blachowski et al., 2009; Milczarek, 2011). In other areas, like the area of the flooded Siersza mine, the measurements, unfortunately, were not carried out. Instead, despite changes occurring in the Polish underground mining industry so far, no large scale analyses of the ground surface deformations due to the mine workings flooding have been performed. The lack of Polish experience in this field, and in particular at the determination of coefficient dm value, forced the report authors to use the value determined for the Ruhrkohle basin.

The calculations of the ground surface deformation for the closed Anna mine were carried out using solutions presented in Sroka's method [20]. For the uplift prediction due to mine flooding, the calculations were carried out for the following parameters of Sroka's method:

$$\overline{\gamma_w} = 10.8\, gon$$

$$d_m \cdot \lambda = 1.2 \cdot 10^{-2} m^2/MN$$

The use of values of $\overline{\gamma_w} = 10.8\, gon$ and $d_m \cdot \lambda = 1.2 \cdot 10^{-2} m^2/MN$ in the forecasting calculations for the Anna mine area seems to be right on the basis of long-term research, deformation forecasts, their verifications (Sroka et al., 2016, 2017) and similarities, in terms of geology, mining conditions, mining technologies as well as deformation forecasting methods, between Polish and German mining regions.

In the first scenario, there is an assumption that only the Anna mine is flooded to the depth of -800 m a.s.l. In this case, considerations have been taken for all longwall panels below the estimated underground water level. Twenty-seven longwall panels were selected for the simulation. The results of the simulation have been presented in the form of the map shown in Figure 5. Also, selected longwall panels and faults in the area of consideration have been marked.

In the second scenario, it is assumed that during the flooding of the Anna mine, there is the possibility of uncontrolled water overflow to the neighboring Rydułtowy mine. In this case, considerations have been taken for all longwall panels below the estimated underground water level. Sixty-nine longwall panels were selected for the simulation. The results of the simulation have been presented in the form of a map in Figure 6. Also, selected longwall panels and faults in the area of consideration have been marked.

In the third scenario, the situation of controlled flooding of the Anna mine and Rydułtowy mine to the depth of -720 m a.s.l. has been analyzed. In this case, considerations have been taken for all longwall panels below the set underground water level. Eighty-seven longwall panels were selected for the simulation. The results of the simulation have been presented in the form of a map in Figure 7. Also, selected longwall panels have been marked, as well as faults in the area of consideration.

From the above, the scenarios with the maximum uplift were:

- Scenario 1 – 19 mm (fig. 5),
- Scenario 2 – 43 mm (fig. 6),
- Scenario 3 – 65 mm (fig. 7).
- As mentioned earlier, deformations resulting from the liquidation of underground mines by flooding are smaller in value compared to surface subsidence resulting from mining exploitation. However, as shown in Figures 5–7, the range of influence is much greater. In the case of scenario 1, the impacts generated from the flooding affected an area with a radius of 4.5 km. In the second and third scenarios, these areas increased to include a 5.5 km (scenario 2) and 10.5 km (scenario 3) radius, respectively. Although vertical deformations resulting from flooding of the underground excavations are not large, due to the range of influence they are also related to objects that are unsecured on the impact of mining exploitation. For this reason, buildings and infrastructure located on the land surface may be damaged. Such damage cases have already been observed several times in Germany and Belgium (Baglikow, 2011; K. Heitfeld et al., 2003).
- The situation is more complicated if discontinuous deformation is taken into consideration. As is shown

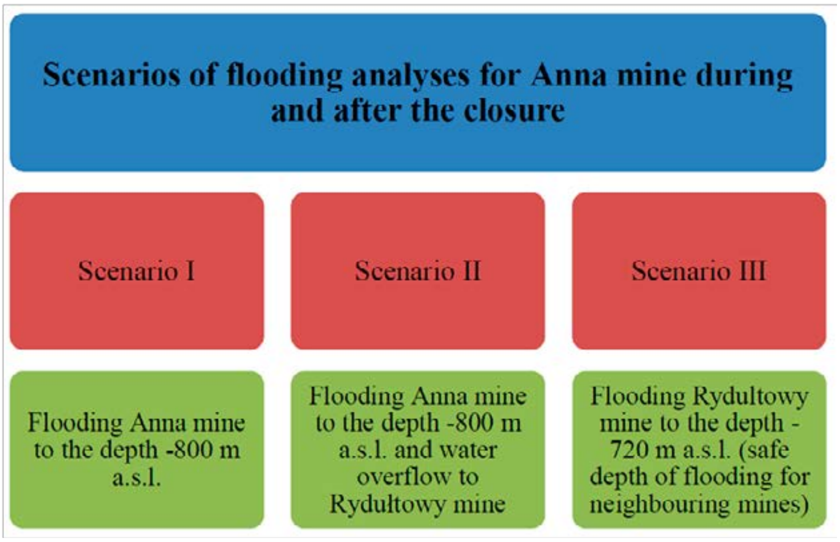

Fig. 4. Anna mine flooding scenarios

in Figures 5–7, there are a lot of faults located in the analysed region. The presence of the water in the neighbourhood of the fault connected with uplift deformation can lead to its activation, which may appear on the land surface in the form of discontinuous deformation such as steps, cracks, etc. (Gudmundsson et al., 2010; Liu, 2020; Sattari & Eaton, 2014). Such cases have also been observed in Europe, especially during the liquidation of German mines (Baglikow, 2011; M. Heitfeld et al., 2016; Schaefer, 2007).

Discussion

Analytical models are typically formulated to capture the behavior of idealized, homogeneous systems or small deviations from the idealized situations, which are expressed as linear terms of a variable that describes the departure from uniformity. Analytical models are characterized by their flexibility and portability. It is therefore easy to reconstruct and requires a small amount of initial data. For this reason, it allows you to simply analyze the phenomena and obtain

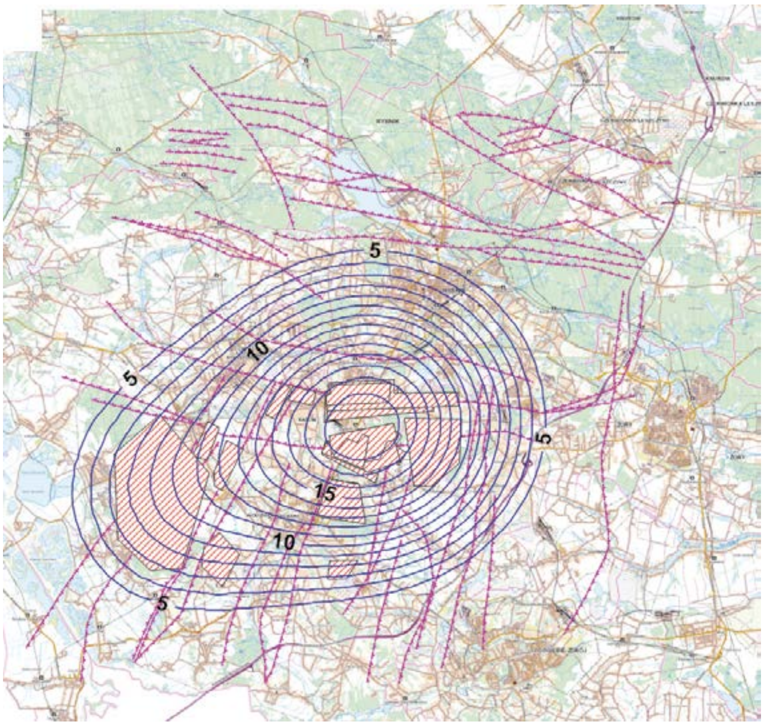

Fig. 5. Predicted ground surface uplift [mm] for scenario 1 – flooding Anna mine to the depth of -800 m a.s.l (blue line – uplift; red diagonal line – flooded longwall panels; magenta line – faults)

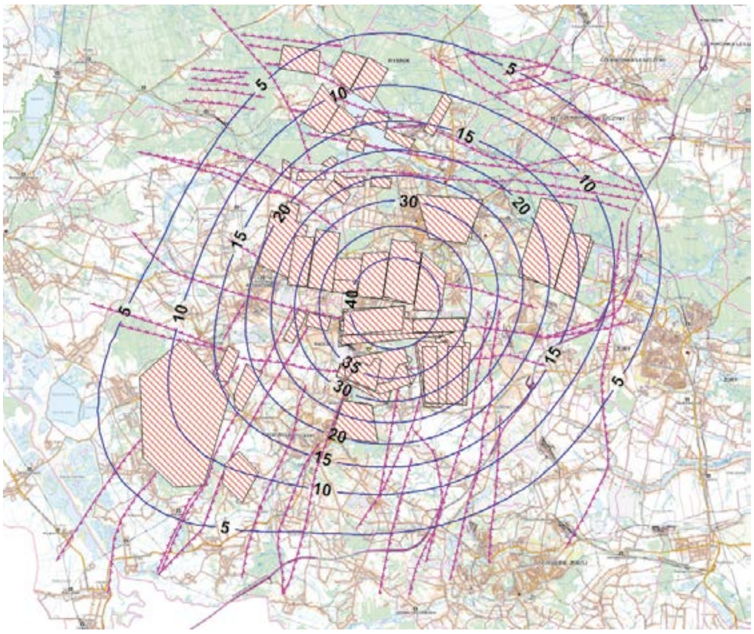

Fig. 6. Predicted ground surface uplift [mm] for scenario 2 – flooding Anna and Rydułtowy mine to the depth of -800 m a.s.l (blue line – uplift; red diagonal line – flooded longwall panels; magenta line – faults)

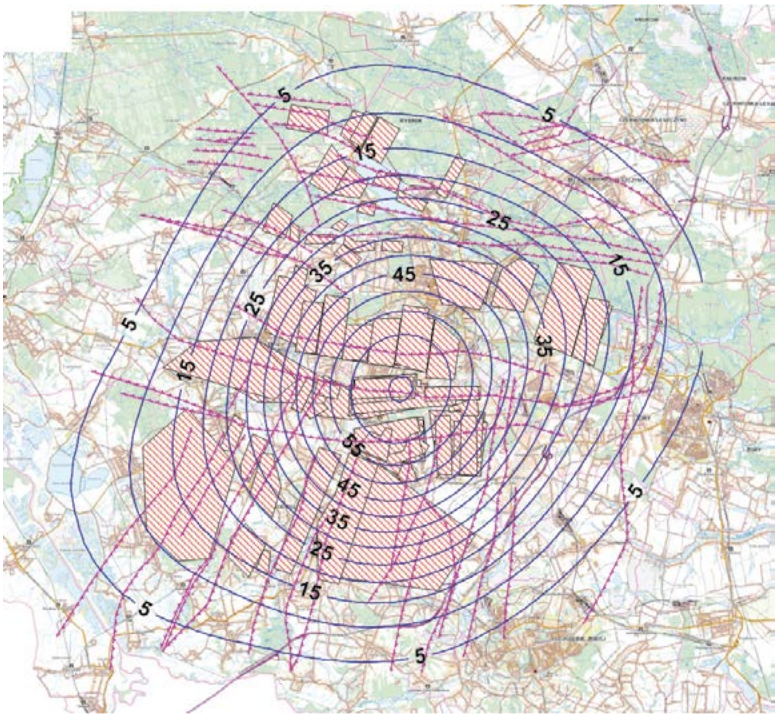

Fig. 7. Predicted ground surface uplift [mm] for scenario 3 – flooding Anna and Rydułtowy mine to the depth of -740 m a.s.l (blue line – uplift; red diagonal line – flooded longwall panels; magenta line – faults)

information through simple calculations needed in the next stage of the project. Analytical models can be created quickly, and the computational cost is low. These analytical methods are easy to use and require a minimal amount of data.

Sroka's forecasting model belongs to the group of analytical models. It is based on a few coefficients that can be simply estimated, e.g., based on land surface measurements (the so-called calibration, model sensitivity testing). As with any method, it also has disadvantages. It is used for deformation analysis and does not allow for other important calculated parameters of the rock mass (e.g. the stress state in the model). It does not account for the parameters of the rock mass directly, as in the case of numerical models.

However, analytical methods, such as this method, allow for relatively fast, adequately precise qualitative estimation of surface deformation indicators for large mining areas. Of course, numerical methods have also been used in the description of the uplifting phenomenon, but due to their limitations, e.g., the size of the model, which significantly increases the number of elements and calculation time, it is necessary to know the appropriate number of physical and mechanical parameters of rock layers. Analytical methods make it easier and faster, providing the use of quality and appropriate results, which can then accurately estimate the deformation of the land surface.

The scenarios presented in the article were selected for analysis as the most probable concerning the Anna mine and the future plans of the mining enterprise PGG S.A. The rock mass deformation analyses were carried out in three scenarios. One concerned the impermeable fault (information from employees of the Anna mine), and the other two assumed the penetration of the material filling the Rydułtowy fault and the overflow of groundwater to the neighboring mines. The last two scenarios may seem unnecessary, but due to many years of mining operations in the fault area and the accompanying seismic phenomena, a „worst-case" should be adopted to minimize subsequent mining damage and the formation of discontinuous deformations. Such a procedure reduces the level of risk and also increases the level of safety.

The analyses carried out for the Anna mine area show a low level of risk for surface objects. However, the scenarios themselves do not assume the closure of the mine as a whole, but only of a few lowest levels of the Anna mine. From the authors' many years of experience from working on scientific projects on German mines, it can be observed that when a mine had been flooded to a depth closer to the surface (e.g. -100m above sea level), it resulted to surface deformation and high deformation index values (uplift even to 0, 50m). The impact on a building structure located on the land surface of a mine that was liquidated by flooding was observed in the Ibbenbüren mine in Germany (Dudek et al., 2020, 2021). This mine was used as an example by the authors. The most important thing to note was that the building structure was outside the zone of main mining influences, resulting from exploitation (flooding influences are characterized by a range of up to 3 times greater). The negative impact of the uplift on the structural elements of the building was noted, which may lead to the whole structure damage.

Conclusions

The growing tendency to close underground coal mines forces both mining entrepreneurs, state administration and scientists to solve environmental and socio-economic problems. In the article, the authors focused on solving the problem of forecasting possible deformations of the land surface with the planned liquidation of the KWK Anna mine. Calculations for 3 scenarios of possible flooding levels of the mine, which were agreed with the employees of the mine, were presented. As a result of the calculations, the distribution of vertical displacements of the land surface was obtained, which differ in both the value of the maximum lift and the range of the impact area. The information presented may be the basis for assessing the possible effects of land surface deformation changes on building structures. This applies in particular to the facilities currently located outside the mining area, i.e., the area where the negative impact of mining activities covered by the concession is possible. As shown in the article, the area established for mining operations is significantly enlarged (two or three times), which means that a large group of objects not protected against mining damage will be subjected to additional deformations.

This information should be taken into account when planning the flooding of underground mines, both in construction activities and in terms of social and economic aspects. Due to the tendency to close underground mines, scientists have to face the challenge of proposing the liquidation of underground workings, especially by flooding them, as it is currently the most popular method. However, forecasting impacts on the rock mass and the surface with precise accuracy is possible, which was presented in this article.

The above-mentioned process of coal mines flooding, resulting from, for example, discontinued drainage of the rock mass, leads to several risks for surface objects and underground infrastructure. These hazards result from the movements of rock mass, which are generated as a result of the performance of mine liquidation, and more precisely, changes in the geomechanical parameters of saturated rocks and changes in pressure (e.g., hydrostatic buoyancy in caved zones).

The resulting uplifting movements can also lead to the creation of much more dangerous phenomena involving discontinuous deformations. The latter is a particular threat to buildings located on the land surface in the region of the mine that is being liquidated. This is why the ability to predict the movements of rock mass generated as a result of shutting down a mine by flooding is key to the protection of the land surface and buildings present thereon. There are already known examples in which the effects of liquidation activities manifested themselves on the land surface in the form of discontinuous deformations of the surficial or linear type. It even happens as a result of upward movements and the fracturing of strong rock strata. It was also possible to record dynamic interactions in the form of tremors.

Acknowledgments

Part of the work presented in this paper has been performed within the MERIDA project (Management of Environmental Risks During and After mine closure) supported by the Research Fund for Coal and Steel (RFCS) under the Contract No. RFCS-CT-2015-00004 and by the Polish Ministry of Science and Higher Education under the Contract No. 3582/FBWiS/2016/2

References

Álvarez, R., Ordóñez, A., De Miguel, E. & Loredo, C. (2016). Prediction of the flooding of a mining reservoir in NW Spain. *Journal of Environmental Management*, 184, 219–228. DOI: 10.1016/j.jenvman.2016.09.072

Baglikow, V. (2011). Damage-relevant effects of mine water recovery – conclusions from the Erkelenz hard coal district. *Markscheidewesen*, 118, 10–16.

Bekendam, R.F. & Pöttgens, J.J.E. (1995). Ground movements over the coal mines of southern Limburg, The Netherlands, and their relation to rising mine waters. 5tfh International Symposium on Land Subsidence, 3–12.

Blachowski, J., Cacoń, S., & Milczarek, W. (2009). Analysis of post-mining ground deformations caused by underground coal extractions in complicated geological conditions. *Acta Geodyn*. Geomater, 6(3), 351–357.

Caro Cuenca, M., Hooper, A.J. & Hanssen, R.F. (2013). Surface deformation induced by water influx in the abandoned coal mines in Limburg, The Netherlands observed by satellite radar interferometry. *Journal of Applied Geophysics*, 88, 1–11. DOI: 10.1016/j.jappgeo.2012.10.003

Devleeschouwer, X., Declercq, P.Y., Flamion, B., Brixko, J., Timmermans, A. & Vanneste, J. (2008). Uplift revealed by radar interferometry around Liège (Belgium): a relation with rising mining groundwater. Proceedings of Post-Mining 2008, 1–13.

Dudek, M., Rusek, J., Tajduś, K. & Słowik, L. (2021). Analysis of steel industrial portal frame building subjected to loads resulting from land surface uplift following the closure of underground mines. *Archives of Civil Engineering*, 67(3).

Dudek, M., & Tajduś, K. (2021). FEM for prediction of surface deformations induced by flooding of steeply inclined mining seams. *Geomechanics for Energy and the Environment*, 100254. DOI: 10.1016/j.gete.2021.100254

Dudek, M., Tajduś, K., Misa, R. & Sroka, A. (2020). Predicting of land surface uplift caused by the flooding of underground coal mines – A case study. *International Journal of Rock Mechanics and Mining Sciences*, 132, 104377. DOI: 10.1016/j.ijrmms.2020.104377

Fenk, J. (2000). *An analytical solution for calculating urface heave when flooding underground mine workings* , 107, 4220–4422.

Gudmundsson, A., Simmenes, T.H., Larsen, B. & Philipp, S.L. (2010). Effects of internal structure and local stresses on fracture propagation, deflection, and arrest in fault zones. *Journal of Structural Geology*, 32(11), 1643–1655. DOI: 10.1016/j.jsg.2009.08.013

Heitfeld, K., Heitfeld, M., Rosner, P. & Sahl, H. (2003). *Controlled mine water increase in Aachen and Sudlimburg stone coal district.* 5. Aachener Bergschandemkundliches Kolloquium, 71–85. (in German)

Heitfeld, M., Rosner, P. & Mühlenkamp, M. (2016). Gutachten zu den Bodenbewegungen im Rahmen des stufenweisen Grubenwasseranstiegs in den Wasserprovinzen Reden und Duhamel. Bewertung des Einwirkungspotentials und Monitoring Konzept-Anstieg bis – 320 m NHN.

Heitfeld, M., Rosner, P., Mühlenkamp, M. & Sahl, H. (2004). Bergschäden im Erkelenzer Steinkohlenrevier. 4. Altbergbaukolloquium, 281–295.

Jakubick, A., Jenk, U. & Kahnt, R. (2002). Modelling of mine flooding and consequences in the mine hydrogeological environment: flooding of the Koenigstein mine, Germany. *Environmental Geology*, 42(2–3), 222–234. DOI: 10.1007/s00254-001-0492-9

Jewartowski, T., Mizerka, J. & Mróz, C. (2015). Coal-Mine Liquidation as a Strategic Managerial Decision: a Decision-Making Model Based on the Options Approach / Archives of Mining Sciences, 60(3), 697–713. DOI: 10.1515/amsc-2015-0046 (in Polish)

John, A. (2021). Monitoring of Ground Movements Due to Mine Water Rise Using Satellite-Based Radar Interferometry – A Comprehensive Case Study for Low Movement Rates in the German Mining Area Lugau/Oelsnitz. Mining, 1(1), 35–58. DOI: 10.3390/mining1010004

Knothe, S. (1984). Prognozowanie wpływów eksploatacji górniczej.

Wydawnictwo Śląsk (in Polish).

Kołodziejczyk, P., Musioł, S. & Wesołowski, M. (2007). *Ability to forecast mining area uplift as a result of mine flooding.* 63(9), 6–11.

Kowalska, I. J. (2014). Risk management in the hard coal mining industry: Social and environmental aspects of collieries' liquidation. *Resources Policy*, 41, 124–134. DOI: 10.1016/j.resourpol.2014.05.002

Krzemień, A., Suárez Sánchez, A., Riesgo Fernández, P., Zimmermann, K. & González Coto, F. (2016). Towards sustainability in underground coal mine closure contexts: A methodology proposal for environmental risk management. *Journal of Cleaner Production*, 139, 1044–1056. DOI: 10.1016/j.jclepro.2016.08.149

Liu, D. (2020). A numerical method for analyzing fault slip tendency under fluid injection with XFEM. *Acta Geotechnica*, 15(2), 325–345. DOI: 10.1007/s11440-019-00814-w

Management of environmental risks during and after mine closure, Contract No. RFCR-CT-2015-00004. (2020).

Milczarek, W. (2011). *Analysis of changes in the rock mass surface after mining in a selected area of the former Wałbrzych Basin. Wroclaw University of Science and Technology. (in Polish).*

Mróz, T.M. & Grabowska, W. (2021). The use of geothermal energy in co-generated heat and power production in Poland – a case study. *Archives of Environmental Protection*, 47(3), 82–91. DOI: 10.24425/aep.2021.138466

Pöttgens, J.J.E. (1985). Bodenhebung durch ansteigendes Grubenwasser. 6. Internationaler Kongress Für Markscheidewesen, 928–938.

Preuβe, A., Kateloe, H.J. & Sroka, A. (2013). Subsidence and uplift prediction in German and Polish hard coal mining. *Markscheidewesen*, 120, 23–34.

Samsonov, S., D'Oreye, N. & Smets, B. (2013). Ground deformation associated with post-mining activity at the French–German border revealed by novel InSAR time series method. *International Journal of Applied Earth Observation and Geoinformation*, 23, 142–154. DOI: 10.1016/j.jag.2012.12.008

Sattari, A. & Eaton, D. (2014). Finite element modelling of fault stress triggering due to hydraulic fracturing. GeoConvention 2014: FOCUS Adapt, Refine, Sustain.

Schaefer, W. (2007). *Ground movements in the tectonics of the Rhenish lignite mining area,* 215–225. (in Polish).

Sroka, A. (2005). Ein Beitrag zur Vorausberechnung der durch den Grubenwasseranstieg bedingten Hebungen. 5. Altbergbau-Kolloquium, 453–462.

Sroka, A., Preuβe, A., Tajduś, K. & Misa, R. (2016). Gutachterliche Stellungnahme zum Einfluss möglicher Grubenwasser-regulierungsmaßnahmen auf die Abwasserinfrastruktur der Emschergenossenschaft Teil 1/1: Markscheiderische Beurteilung.

Sroka, A., Tajduś, K. & Misa, R. (2017). Gutachterliche Stellungnahme zur Auswirkung des Grubenwasseranstiegs im Ostfeld des Bergwerkes Ibbenbüren auf die Tagesoberfläche.

Tajduś, A. & Tokarski, S. (2020). Risks Related to Energy Policy of Poland Until 2040 (EPP 2040). *Archives of Mining Sciences,* 877–899.

Tajduś, K., Sroka, A., Misa, R. & Dudek, M. (2017). *Examples of threats to the ground surface with discontinuous deformations of the surface type appearing over liquidated underground mining excavations,* 19(3), 3–10. (in Polish).

Vervoort, A. & Declercq, P.-Y. (2017). Surface movement above old coal longwalls after mine closure. *International Journal of Mining Science and Technology*, 27(3), 481–490. DOI: 10.1016/j.ijmst.2017.03.007

Vervoort, A. & Declercq, P.-Y. (2018). Upward surface movement above deep coal mines after closure and flooding of underground workings. *International Journal of Mining Science and Technology*, 28(1), 53–59. https://doi.org/10.1016/j.ijmst.2017.11.008

Wasielewski, R., Wojtaszek, M. & Plis, A. (2020). Investigation of fly ash from co-combustion of alternative fuel (SRF) with hard coal in a stoker boiler. *Archives of Environmental Protection*, 46 (No 2), 58–67. DOI: 10.24425/aep.2020.133475

Wesołowski, M. (2012). *Computer simulation of the impact of flooding mine workings of the former mine "Gliwice" and "Pstrowski" on land surface,* 68(5), 54–59. (in Polish).

Wysocka, M., Skubacz, K., Chmielewska, I., Urban, P. & Bonczyk, M. (2019). Radon migration in the area around the coal mine during closing process. *International Journal of Coal Geology*, 212, 103253. DOI: 10.1016/j.coal.2019.103253

Zwierzchowski, R. & Różycka-Wrońska, E. (2021). Operational determinants of gaseous air pollutants emissions from coal-fired district heating sources. *Archives of Environmental Protection*, 47(3), 108–119. DOI: 10.24425/aep.2021.138469

Deformacja powierzchni terenu spowodowana likwidacją kopalni Anna przez zatapianie

Streszczenie: Najbardziej znaną na świecie metodą likwidacji podziemnych kopalń węgla kamiennego jest samoistne zatopienie jej w wyniku zaprzestania odwadniania górotworu. W związku z hydrologiczną odbudową zaburzonego wcześniej systemu wodnego przez eksploatację górniczą, pojawiają się ruchy górotworu o kierunku przeciwnym do osiadania. Ruchy nazywane są wypiętrzaniem masywu skalnego. Celem artykułu jest przedstawienie możliwych zagrożeń związanych z obiektami budowlanymi zlokalizowanych na powierzchni terenu oraz środowiskiem, jakie mogą wystąpić podczas zatapiania kopalni podziemnej. Kwestia prawidłowego prognozowania tego zjawiska była dotychczas w literaturze światowej marginalna. Do tej pory wykorzystano tylko kilka metod analitycznych do przewidywania możliwych skutków deformacji powierzchni ziemi. Obecnie najbardziej docenianą analityczną metodą prognozowania deformacji powierzchni spowodowanych likwidacją podziemnych wyrobisk przez zatapianie jest metoda Sroki. W artykule autorzy przedstawili analizę scenariuszy likwidacji opracowanych dla polskiej kopalni i ich wpływu na powierzchnię terenu oraz środowisko. Przedstawione w rękopisie scenariusze zostały wybrane do analizy jako najbardziej prawdopodobne ze względu na działalność kopalni i przyszłych planów przedsiębiorstwa górniczego. Proces zatapiania kopalń podziemnych powoduje szereg zagrożeń dla obiektów naziemnych i infrastruktury podziemnej. Dlatego należy prognozować wypiętrzenie spowodowane likwidacją kopalni przez zatapianie. Powstające ruchy podnoszące mogą również, poza ciągłą deformacją, prowadzić do powstania znacznie groźniejszych zjawisk związanych z deformacjami nieciągłymi.