Secondary Water Saturation of a Carboniferous Rock Mass in a Abandoned Mines as the Cause Behind the Changes in Geomechanical Conditions and State of Hazards in Active Mines of the Upper Silesian Coal Basin

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Abstract

Mining activity, from the phase of exploration of the rock mass to the end of exploitation and abandonment of the mine, causes destruction of the rock mass and its dewatering This is the resulting in changes of the original geomechanical properties of rocks and their strengthening during and after dewatering. These changes, in turn, affect the formation and an increase in number of manifestations of the main natural hazards (fire, gas, induced seismicity and rock bursts). The current mining situation in the Upper Silesian Coal Basin (USCB) causes that the active and abandoned mines coexist in the close vicinity. The process of flooding of the abandoned mines is ongoing up to re-saturation of rocks with water. It changes the geomechanical, and thus form the hazardeous conditions. Some hazards (fire, gas, tremors and rock bursts) are limited, on the other hand among other hazards, it occurs an increase in symptoms (hazards: uncontrolled methane escapes, water, environmental, common like sinkhole, and other geomechanical ones, e.g. collapse). The reason for these changes, e.g. in the case of water hazards, may be the changes in the geomechanical properties of rocks, and conditions of safety measures, for example safety pillars or water dams. As presented in the article on the example of a safety pillar, the results of geomechanical research can be used for the design of safety measures.

Keywords: USCB, rock mass, rocks, mechanical properties, hydrogeological properties

Introduction

At different stages of development of hard coal mining in the USCB, various dependencies of mining activities and closure of mines were observed, with hydrogeological and geomechanical conditions changing in the life cycle of the mine. The changes in conditions of mining exploitation are strongly diversified in different phases of the mine operation, and also depend on the state of mining technologies, varying over time. On these changes, which rely initially on dewatering of the rock mass and the change in the rock properties, then on flooding of the abandoned mines and its effect on the rock properties, depend largely on the type, nature and intensity of mining hazards and environmental threats (Grmela, Rapantova 2002).

Characteristics of changes in hydrogeological and geomechanical conditions and development of natural hazards in the life cycle of the mine

The effect of variability in hydrogeological conditions and water saturation on the geomechanical conditions of the rock mass is presented schematically in 8 steps of mining activity development. The development of natural hazards and conditions determining the state of the rock mass has been considered in the system: *hazards – sources and reasons – geomechanical and hydrogeological conditions and their changes*. The sequence of hazards assumed below reflects the significance of the hazard in a given phase of the mine development (from dominant to marginal), including:

1) **at the stage of exploration of rock mass before construction of the mine** – lack of more important natural hazards of larger scale and substantial effects, except for gas and environmental hazards – hazards related to the process of the rock mass exploration and execution of drilling works to investigate the deposit (phase of hazards identification and assessment) – original state of the rock mass, undisturbed rock mass, at great depths triaxial compression stress state, under natural conditions of saturation and properties of the rocks,
2) **at the stage of construction of the mine** the following hazards may occur: water, geomechanical, geotechnical, as well as gas and environmental – these hazards are usually associated with first mining works and opening the deposit to the mining activity – state of the rock mass is predominantly close to triaxial compression stress state, under the near to natural strength-strain and hydrogeological properties of the rocks, the inflow of water to the excavations from static resources increases, the development of cone of depression occurs,
3) **at the stage of development of operation**, the following hazards may occur: geomechanical including induced seismicity of lower energy, and less frequently rock burst, geotechnical, water, gas, fire, dust and environmental – associated with the intensification of dewatering and drainage, process of the dewatered rock mass strengthening and increasing the depth of exploitation, and the spread of excavations. State of the rock mass is complicated and very changeable and dependent on actual mining activity and in close vicinity of excavations it changes from a triaxial compression stress state into a biaxial one, and in the vicinity of the pillars into a uniaxial one, an increase in strength and a reduction of rocks deformability, an increase in water inflow from static resources and small inflow from dynamic resources, an increase in degree of drainage and water absorption of the rocks, humidity strives to capillary saturation state and static resources of the water decrease, a clear destruction of the rock mass causes connectivity of aquifers - a cone of depression develops vertically and horizontally,
4) **at the stage of the mature phase of the mine development**, the following hazards may occur: tremors and rock bursts, other geomechanical, gas, fire, dust, climatic and environmental – the water hazard loses its importance and it is mainly related to underground sources (underground reservoirs, boreholes, fault zones), associated with strong drainage of the rock mass from water. State of the rock mass: clear strengthening of rocks, while reducing their deformability, and at the same time, strong transformations associated with intensive influence of mining and transition of the rock mass into a uniaxial compression stress state, or intermediate between uniaxial and triaxial one, an inflow of water to excavations from static and dynamic resources is balanced, an inflow from dynamic resources increases and the degree of drainage of rocks increases, approaching it to the value of specific yeld coeficient, water capacity of rocks approaches the maximum values, humidity of the rock mass approaches the value of capillary saturation state, static water resources are substantially reduced, the shaped cone of

depression strives to reach its maximal range,

5) **at the final stage of mining activity**, the following hazards may occur: tremors and rock bursts, other geomechanical, gas, fire, dust, climatic and environmental - in the conditions of drained rock mass, and great depth and range of the cone of depression, water hazard occurs but of marginal importance - it is mainly related to the loss of precaution and human factor (a source may be: underground reservoirs, boreholes, fault zones, and technical state of the drainage system) – they are associated with a clear strengthening of rocks and the rock mass, as a result of dewatering, but also with strong destruction processes. State of the rock mass: with high strength, low deformability of rocks and transition of the rock mass into biaxial or uniaxial state, or the state close to them, inflow of water comes from disappearing static resources, and predominant dynamic resources and its intensity decreases and stabilizes, the degree of drainage approaches the value of specific yeld coefficient and water capacity of rocks reaches the maximum values, humidity of the rock mass reaches approximately the values of capillary saturation state of rocks, static water resources are substantially reduced, the maximum range of the cone of depression is stabilized vertically and horizontally,
6) **at the closure stage**, the following hazards may occur: uncontrolled mine gases migration, fire, water and geomechanical, geotechnical, less frequently low-energy seismicity and environmental, the role of water hazard increases, which is related to errors in the adopted conceptual model of the mines drainage and in the mine abandonment scenario (important source: underground reservoirs, boreholes, water filled excavations, fault zones, water supply sources, exposed: surface of the terrain, active mine workings, drainage system, active shafts, inclined slopes and inclines as connections with the surface) - they are associated with a clear strengthening and low deformability of the rocks. State of the rock mass - strongly loosened transits into the state close to uniaxial states, or similar to it, stabilized minimal inflow of water from dynamic resources, depleted static water resources, maximal capacity of dewatered spaces, maximal degree of drainage and water capacity of rocks, humidity of the rock mass minimal, close to the state of capillary saturation of rocks, the range of the depression cone vertically and horizontally maximal,
7) **after closure and partial flooding** as well as in the process of stationary or even deep water drainage (submercible system), the following hazards may occur: water hazard for own drainage systems in closed mine and for safety in active mines in vicinity, geomechanical, among them less frequently seismicity, common (sinkhole, uncontrolled mine gases migration)environmental, gas, fire – hazards are related to erroneous safety assumptions, errors in the mine flooding conceptual model and hydraulic model, errors in the mine abandonment scenarios. State of rock mass, determined by occurrence of three zones of flooding (entire flooding, transition states on the level of water table, and the secondary state of saturation due to flooding – Bukowski 2010), state as in the phase 6, and additionally in the flooded part of the mine: re-saturation and clear weakening of the rocks by water, and increasing their deformation (Bukowska 2015a,b, Li et al., 2005), especially on the level close to water table and in the area of boundary and safety pillars, dams and insulation plug, etc. – possible changes in directions and intensity of flow, blurring and soddening of rocks, a decrease in water capacity of free voids in the mining excavations, possible reactivation of goaf, pushing out the mine gases towards the surface, physical and chemical changes of waters, including "first flush" effect (Younger 1997, Younger, Wolkersdorfer 2004), an increase in pressures and differential water pressures in the reservoirs, an increase of hydraulic gradient in the border areas and saturation of the rock mass by water, including one-sided saturation of the boundary and safety pillars, transition of the rock mass under water from the uniaxial state to close to the hydrostatic state, saturation

state – zero degree of drainage and water absorptivity of the rocks, a reduction or cessation of water inflow below the water level and a clear reduction in the diameter of the cone of depression,

8) **after complete water table rebound, the following hazards in abandoned mines** may occur: common and environmental, gas and fire, with low residual seismicity, implicating reactivation of goaf, shaft backfillings, damage to the pillars subjected to water influence, and water hazard for neighbouring mines etc., associated with the geomechanical and geotechnical processes, processes of re-saturation of the rock with water and pressure recovery. It is related to erroneous assumptions for safety, errors in the assessment of geological and mining conditions, properties of the rock environment covered by water table rebound processes, errors in the model of flooding of the mine and the method of the end of drainage, errors in determination of conditions of water circulation and hydrodynamic model, water quality and position of water piling up ordinate, errors in the mine abandoning scenarios. Exposed: surface of terrain, abandoned, backfilled and unabandoned, unbackfilled shafts, and boreholes, neighbouring mines and deposits intended for exploitation, investments based on the underground infrastructure of the abandoned mine and on water and mine gas. State of rock mass – state of saturation close to original – description as for step 7 below the water table.

As it results from the above, the change in hydrogeological and geomechanical conditions occurs at every stage of the mine's operation, while the changes in the hydrogeological conditions in a large approximation are inversely proportional to the changes in geomechanical conditions. Both changes, in the hydrogeological conditions including changes in flooding of mines, as well as the changes in geomechanical conditions, if they are not a direct cause of water hazards, tremors and rock bursts, roof colapse and sinkhole, largely indirectly shape these and other natural hazards in the underground mine, from the beginning of mining.

Interdependence of geomechanical and hydrogeological conditions and their effect on the state of hazards to active mines

The evaluation of the relationship between hydrogeological and geomechanical conditions, as well as the assessment of their effect on the formation of various hazards, are based on analytical, geophysical, drilling, etc. methods of testing. In every case, the key to such an assessment are analyzes of changes in geological and mining situations and conditions, based on observations and results of hydrogeological and geomechanical studies of the rocks and rock mass. Progressing since the 1990s in Poland, and in the Czech Republic, abandonment of unprofitable mines, is most often associated with their partial or total flooding, with water from the natural inflow. Regardless of the course and rate of this process in the abandoned mines in Poland, most often bordering with the active mines (Figure 1), there arise huge water reservoirs, with capacity counted in millions of cubic meters of water. These reservoirs constitute a serious source of hazard to the active mines, operating in their vicinity.

An important element of a prognosis of the mines flooding is an assessment of the possibility of water flow from one mine to the another one. It is necessary to determine critical parameters of the protections, e.g. safety pillars, and condition and transmisivity for all hydraulic connections. The safety of active mines operation, located in the vicinity of the flooded mines depends on correctness in determining above-defined conditions (Figure 1). In the USCB coal mines, the dimensions of safety pillars are determined in adaptation to the mining situation, based on the examined geomechanical properties of the rocks that build them. For this assessment, the so-called theory of limit range of excavations is used, as well as the Russian calculation formulas according to Slesariev, adapted to Polish conditions (vide Konstantynowicz et al. 1974, Maksimov 1967). However, due to the repeated changes in saturation of rocks of the disturbed rock mass in the vicinity of mining excavations and within the rock debris in the goaf (occurring at different rates in phases 6 ÷ 8), necessary corrections have to be introduced.

The loosened water-absorptive rocks within disturbed rock mass are saturated with water from the air-dry state and then capillary saturation, to the saturation state, while the non-water-absorptive rocks are surface wetted and subjected to the processes of blurring and soddening. Considering the occurrence of constant vertical pressure of the rock mass of value resulting from the depth and density of the above rock mass, and the reduction in rock strength due to the destruction and effect of water, it is necessary to consider these processes e.g. in calculating the critical dimensions of the safety pillars. The calculation formulas developed in Russia had been proved in mining practice and in their application since the 1970s in Poland and the Czech Republic. Then, the conditions for conducting laboratory tests of the rocks (in the air-dry state) were adapted to the condition of the rock mass, described in phases 2 ÷ 5 of the mine development. It was not until the first decade of the 21st century, despite performing earlier tests for different humidity states, that an attempt was made to relate the results of strength-strain determinations to the moisture content state close to the natural one (Bukowska Kidybiński 2002, Bukowski, Bukowska 2008, Bukowska 2015a,b). The broader physical-mechanical laboratory tests were carried out, which indicated the ranges of variability of some of the strength-strain parameters of the USCB Carboniferous rocks, due to their capillary saturation with water. The uniaxial tests were carried out in full stress-strain characteristics, stating that the main loss of compressive strength of rocks (nearly 80-90%) occurs already at the transition of the sample from the air-dry state to the capillary saturation state. The decreasing of compressive strength, depending on the type of rock, for the USCB rocks may vary from a few percent for siltstones, 20-30% for sandstones, to nearly 50% for some claystones. The Carboniferous coals lose their strength on average from a few to about 20% under conditions of water saturation.

As it results from the above, the assessment of physical-mechanical properties of rocks, with the simulation of re-saturating the rock mass with water in the process of flooding of the mine, is of key importance for the border areas. The assessment of stability of safety pillars with the application of different calculation formulas, using the results of strength-strain tests on rock parameters, repeatedly decides about the safety of the neighbouring mine, which conducts mining exploitation. For the conditions of capillary

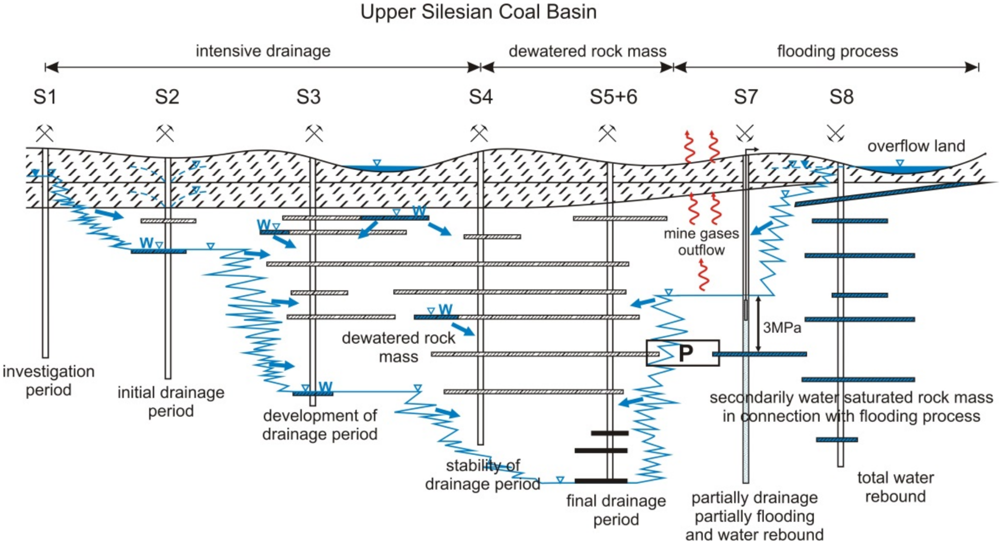

***Figure 1** Scheme of actual hydrodynamic situation of mining in the Upper Silesien Coal Basin and their possibility of influence on geomechanical and hydrogeological conditions and their changes*

saturating with water of the rocks of safety pillars, an example of the calculations according to Slesariev, presented below was used:

$$D = G \times \sqrt{\frac{4p}{\eta \times (\frac{\sigma r}{8})}}$$

D – critical dimension of the pillar in hard coal, m, G – hight of exploitation = 4.0 m, p – pressure of water in the reservoir = 3.0 MPa, σrw – tensile strength of hard coal in capillary saturation state = 0.85 MPa, σrd – tensile strength of hard coal in air-dry condition = 1.15 MPa, η – dimensionless coefficient according to Slesariev – regular deposition =1.33 and variable deposition of layers =2.0,

As can be seen from the above, the critical width of the hard coal pillar for the active mining excavations, with a given operating height and water pressure, at the level of floor of the excavations, made in the area of the reservoir in the abandoned mine, for rocks in the air-dry state will amount to D^d = 25.84 ÷ 31.68 m. The flooding and filtration process will cause saturation of the rock mass between the flooded and dewatered rock mass (Figure 1). It will also reduce the strength of the rocks, separating the active mine from the abandoned one. This is illustrated by the results of calculations contained in Table 1, which indicate the need to consider an increase of about 5-6 m in the critical width of the safety pillar for the planned excavations, or to lower the water table and water pressure in the reservoir in the abandoned mine, to the level safe for the existing pillars. When determining the width of the safety pillar, it is necessary to take into account all hazards and natural conditions, occurring in the given location, as well as the effect resulting from the existing and planned mining exploitation.

Conclusions

Experience, gained in the Polish and Czech co-existing active and abandoned mines, indicate the need to adjust the approach to the assessment of natural hazards, especially the water hazard, to the changing hydrogeological and geomechanical conditions. The process of flooding of the mines undoubtedly changes the geomechanical properties of the rock environment, leading to reduction

***Table 1** Aspects of monitoring tasks*

Slesariev coef. [-]	D^w [m]	D^d [m]
η (1,33)	36,85	31,68
η (2,00)	30,05	25,84

of its strength parameters and to increase of deformability. It makes, that the planning of abandonment of mines and the ordinate of water table in process of water table rebound should be done not only applying the knowledge of mining hydrogeology, as to the hight of water rebound, directions, method and quantity of water flow, but also with the use of knowledge of geomechanics. Interdisciplinary research in this field is the only and modern approach to the assessment of the interaction of risk factors, associated with the change in geomechanical conditions, as a result of the changes in hydrogeological conditions. These studies are used in the planning of monitoring and assessment of potential consequences for the surface area of the abandoned mine and in the assessment of hazards in the active mine, located in the area of the being created, or already created water reservoir.

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References

Bukowska M, Kidybiński A (2002) Influence of natural factors of rock mass on their strength assessed in situ and laboratory methods (in Polish, abstract in English). Scientific works of Central Mining Institute. Mining and the Environment No 1, 35-46.

Bukowska M (2015) Influence of grain size, humidity and state of stress on the mechanical properties of sandstones. Acta Geodynamica et Geomaterialia Vol. 12, No. 2 (178), 187-195.

Bukowska M (2015) Influence of height-to-diameter ratio samples and humidity on the geomechanical properties of sandstones. 15th International Multidisciplinary Scientific Geoconference SGEM 2015. Albena, Bułgaria, Vol III – Exploration and Mining, 391-398.

Bukowski P, Bukowska M (2008) Changes in geomechanical properties of carboniferous rocks under the influence of water and their possible consequences in the areas of abandoned mines in the Upper Silesian Coal Basin Poland 10th Congress Mine Water and the Environment, Karlovy Vary, Czech Rep.

Bukowski P (2010) Predicting the water hazard related to flooding of hard coal mine workings. Science works of Central Mining Institute no 882 (in Polish, abstract in English). Prace naukowe Głównego Instytutu Górnictwa, Studia-Rozprawy-Monografie nr 882, Katowice, GIG.

Grmela A; Rapantova N (2002) Protection of groundwater resources quality and quantity in mining areas . In: NATO-Advanced-Study-Institute on Deposit and Geoenvironmental Models for Resource Exploitation and Environmental Security. Book Series: NATO Science Series, Sub-series 2: Enviroenmental security, Volume: 80: 385-397. WOS:000182552500019

Konstantynowicz E, Bromek T, Piłat T, Posyłek E, Rogoż M (1974) Determination of safety pillars for limiting water hazard in hard coal mines (in Polish, abstract in English and Russian). Prace GIG, Komunikat nr 615. Katowice Central Mining Institute.

Li Z, Sheng Y, Reddish DJ (2005) Rock strength reduction and its potential environmental consequences as a result of groundwater rebound. Procc. Of the 9th IMWA Congress, Mine Closure. Oviedo, Spain. pp. 513-519

Maksimov V M eds. (1967) Spravotshnoje rukovodstvo gidrogiealoga. Izdatielstvo, Niedra

Younger PL (1997) The longevity of minewater pollution – a basis for decision making. Sci Total Environ, 194-195: 457-466

Younger PL, Wolkersdorfer C (2004) Mining Impacts on the Fresh Water Environment: Technical and Managerial Guidelines for Catchment Scale Management. Mine Water and the Environment March 2004, Volume 23, Supplement 1, pp s2–s80