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An assessment of the impact of the degree of the filling of shallow voids on the possibility of sinkhole formation on the surface

Introduction

The formation of sinkholes on the earth's surface poses a significant threat to the safety of people and property. Estimates show that from a few to a dozen or so such sinkholes develop annually in Upper Silesia, but exact statistics are not known. The sinkholes pose a threat to public safety, mainly due to their damaging effects on buildings. Due to frequently missing geological and mining documentation, their development is unpredictable. This is all the more so due to the fact that they develop even over one hundred years after the termination of mining activity. The cost of their removal itself is not high when we take into account that in the case of Poland, the total cost of removing mining damage is between 1%

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and 3% of the cost of hard-coal extraction (Kwiatek 2002). Therefore, it is very important to get to know the mechanism behind the formation of these deformations and to develop correct models for their forecasting as well as identifying ways of eliminating the threat. The cause of the emergence of sinkholes is the loss of stability of shallow voids located at low depths. These voids may be of natural origin or may be related to human activity, namely mining excavations (Chudek et al. 1988; Kratzsch 1983; Whittaker and Reddish 1989). The subject of this paper are sinkholes related to mining activities. They constitute one of the most important forms of the environmental impact of mining, alongside continuous deformations (Kratzsch 1983; Peng 2008, Peng ed. 2020) as well as discontinuous linear deformations (Whittaker and Reddish 1989; Ścigała and Szafulera 2020). The issues related to anthropogenic sinkholes are usually associated with post-mining areas (Kretschmann et al. 2017). However, they should also be associated with areas of active mines, especially those that have been mined continuously for many years. Canbulat et al. (Canbulat et al. 2017) presented an interesting overview of information and research results on the formation of sinkholes. It also includes the results of statistical research on sinkholes that occurred in Newcastle. Exploitation was carried out using a room-and-pillar system. The diameters of the sinkholes ranged from 0.1 m to 25 m, and their depth was from 0.2 m to 15 m. They were formed over workings located at depths from 4 m to 50 m.

Sinkholes caused by mining activities may be associated with the collapse of various types of workings. Strzałkowski and Litwa (Strzałkowski and Litwa 2021) presented appropriate statistical analyses, as a result of which, it was established that in one of the mines of the Upper Silesian Coal Basin, the greatest number of sinkholes is formed above headings (68%), galleries (18%), and in the location of shafts (7%). Analyses were also conducted on the depth of the location of over 300 workings over which sinkholes were formed. Over 98% of these workings were located at a depth of up to 100 m.

Singh and Dhar (Singh and Dhar 1997) made similar observations regarding the depth of mining excavations, the collapse of which causes the formation of sinkholes. Their literature review showed that the sinkholes formed in the US, India, China, and the UK were generated by workings located at depths of up to approx. 100 m. The authors also attempted to present the mechanism of the formation of sinkholes in relation to the structure of the rock mass. An important observation was also the determination of the influence of tectonic disturbances on the possibility of the formation of sinkholes. It also includes a method of filling voids in the rock mass with the use of a hydraulic-pneumatic unit.

Sahu and Lokhande (Sahu and Lokhande 2015) presented the factors influencing the formation of sinkholes, which include: the mining system, the number of exploited seams, the depth of exploitation, the thickness of the seam, tectonic disturbances, the value of stresses in the rock mass, the topography, the construction of the overburden, the groundwater level, precipitation infiltrating overburden rocks, and seismic shocks. They also presented the following division of methods for forecasting the risk of sinkholes:

- empirical method,
- semi-empirical method,

- remote sensing & GIS,
- numerical modelling,
- geophysical method.

In the conditions of Polish coal mining, the following methods are most often used to forecast the formation of sinkholes: the methods of Chudek–Olaszowski, Janusz–Jarosz (Chudek et al. 1988) as well as numerical methods. The first two methods are empirical. Very popular is the method of Chudek–Olaszowski, especially in its simplified version, which allows calculation of the probability of sinkhole formation. To perform the calculations, it is not necessary to know the values of strength parameters of the rocks, but only the thickness of the loose rock overburden, the depth of the void and its height. A growing interest has been reported in the application of numerical modeling based on the methods of finite, boundary and distinct elements (Tajduś et al. 2012).

Bearing in mind the above (frequent application), in the present work, the method of Chudek–Olaszowski was applied as well as the co-author's method (Strzałkowski 2015) for further verification. The said methods are briefly discussed later in this paper.

The works (Strozik et al. 2016; Strozik 2018) present the dangers to the area of Upper Silesia resulting from the existence of former shallow excavations. Strozik (2018) drew attention to the need to fill shallow voids in the rock mass, pointing to ash-water mixtures intended for this purpose as the most suitable material.

Fly ash has many desirable properties, thanks to which, it can be used in many areas, including construction (Ramme and Tharaniyil 2004; Ahmaruzzaman 2010; Yao et al. 2015), agriculture (Basu et al. 2009; Shaheen et al. 2014), and in particular in geotechnical engineering (Pandian 2004; Moghal 2017; Reddy et al. 2018; Bhatt et al. 2019).

The use of fly ash in underground mining is a method of fly ash recovery, which is typical for Polish industry (Uliasz-Bocheńczyk et al. 2015).

The ecologically safe placement of this waste allows not minimization of the risk of sinkhole formation but also avoids the storage of such waste on the surface.

The advantage of the ash-water mixtures used for this purpose are their very good migration properties, allowing the tight filling of the void.

The properties of hydromixtures depend mainly on the physical, chemical, and mineralogical properties of the fly ash, and these in turn depend on the petrographic composition of the combusted coal as well as the technology of its combustion. Therefore, the necessity to select such a composition of the mixture to ensure its appropriate physical and mechanical properties is of particular importance. Works on the possibility of using ashes to prepare such mixtures have already been conducted for many years (Kaniraj and Havanagi 1999; Sebastia et al. 2003; Kim et al. 2005; Mishra 2003; Mishra and Rao 2006; Jiang et al. 2017). Not all fly ashes have the same binding properties. When assessing the ash, the first factor to be taken into account is its fineness and chemical composition, which determine the binding and pozzolanic properties (Joshi and Malhotra 1985; Marsh and Day 1988; Tangpagasit et al. 2005; Agarwal 2006; Thomas 2007; Giergiczny et al. 2013; Strzałkowska 2021).

The pozzolanic activity of most ashes improves with increasing lime content. Gypsum is also used to accelerate pozzolanic reactions (Sivapullaiah and Moghal 2011).

The natural hydraulic activity of fly ash results from the fact that it contains reactive calcium and active silica. Ashes containing more than 7% CaO exhibit binding properties without additional activation. Therefore, the composition of the hydromixture should be established individually for each type of ash. A comprehensive assessment of the possibility of using ash should also take into account its environmental impact. One of the evaluation methods is the analysis of the aqueous extract obtained in the leaching test. Research into energy waste has shown that the content of heavy metal cations in aqueous extracts is low, which proves that they create forms that are insoluble or sparingly soluble in water (Mazurkiewicz 1990; Mazurkiewicz et al. 1997; Kapuściński and Strzałkowska 2005; Szwalec et al. 2017). However, it should be noted that the standard aqueous extract completely ignores the issues of waste kinetics. Some waste releases toxic substances only after some time or under specific conditions (Kapuściński and Strzałkowska 2005; Szwalec et al. 2017; Dudas 1981). An important role in the leaching of fly ash is played by the way in which a given element is present in coal (Izquierdo and Querol 2012). The mobility of most elements present in fly ash also depends on the pH of the environment (Tian et al. 2018).

The most commonly used types of fly ash are in the form of suspensions characterized by, among other things, bulk density in the range of 0.0120–0.0186 MN/m^3, viscosity in the range of 0.006–0.125 Pa s, fluidity in the range of 8–35, and compressive strength after solidification up to 3 MPa (Mazurkiewicz 1990; Mazurkiewicz et al. 1997). In the case of filling voids at a low depth, the compressive strength of the sealing mixture after twenty-eight days should be from 3 to 7 MPa, in some cases even 15 MPa, depending on the type of objects on the ground surface (Strozik 2015). The solidified emulsion formed from fly ash with hydraulic properties resembles cohesive rocks. It is characterized by a lack of slakeability, even after a long period of time, thus the material filling the gaps will not be washed out (the phenomenon of suffosion). If it is necessary to obtain a solidified emulsion with significantly higher mechanical parameters, cement should be added to the initial mixture.

There are several methods of sealing the rock mass by a borehole injection. The paper by Stryczek and Gonet (Stryczek and Gonet 2000) distinguishes classical and pressure injection, and high-pressure injection with hydraulic soil and rock mining – jet grouting. Due to the elimination of voids in the rock mass, classical and pressure injection is of significant importance. High-pressure injection is used to protect existing buildings. Kubański (Kubański 2008) presented a brief overview of technical solutions used to fill shallow voids in the rock mass.

The ash can be injected dry or as water mixtures. Dry injection consists of the creation of pressure boreholes through which the ashes are deposited with the use of a blower, the position of which is set at three depths, which ensures a good filling of the void. Inspection holes are made between the pressure boreholes, allowing the height of the void filling level to be tracked – Figure 1 (Łabanowicz 1976).

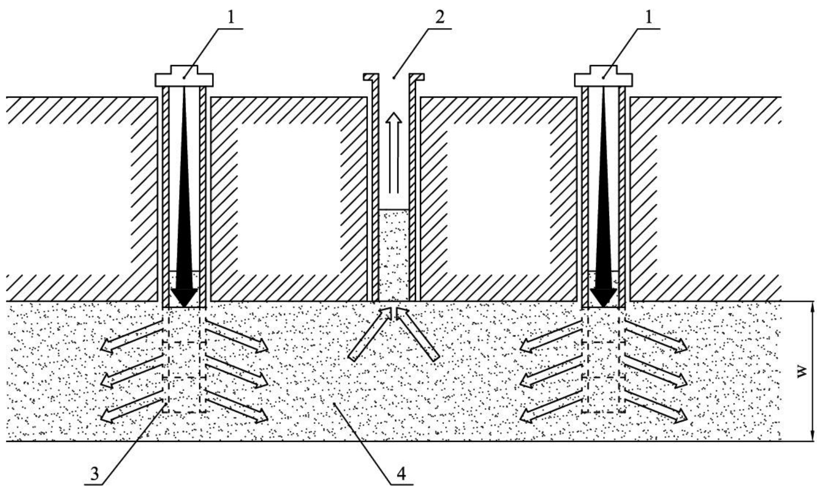

Fig. 1. A method of filling shallow voids by blowing in fly ashes according to (Łabanowicz 1976)
1 – a borehole for pumping dust; 2 – control hole; 3 – perforated pipe; 4 – void with height w

Rys. 1. Metoda zapełniania płytkich pustek za pomocą wdmuchiwania popiołów lotnych

For obvious reasons, it is particularly effective to inject water-ash and water-cement-ash mixtures, which have binding properties and exhibit a certain compressive strength after some time.

The water-cement ratio is a key factor influencing the rheology of the ash-cement slurry. In the case of a high water-cement ratio (1.5), it is a Newtonian fluid (perfectly viscous). The setting time of such a cement slurry can be regulated by temperature (Huang et al. 2021). The rise in temperature results in the reduction of shear stresses in slurry mixtures (Lee et al. 2017). The test results (Mirza et al. 2002) demonstrate that the addition of fly ash to cement slurries improves their strength and rheological properties comparable to those of pure cement slurries that are older in age. The work (Lee et al. 2003) investigated the effect of the particle size distribution of the system fly ash-cement on the fluidity of cement slurries with the use of class F fly ash. It was demonstrated that fluidity increases when the particle size distribution in the system fly ash-cement becomes wider.

The high content of iron oxide, aluminum oxide and other alkaline earth materials in the fly ash causes unfavorable rheological properties; therefore, various surfactants are used which modify the surface properties of fly ash particles (Naik et al. 2011).

The diagram of the installation for injecting ash-water and cement-water slurry, inspired by the work of Kubański (Kubański 2008), is shown below – Figure 2.

As can be seen from the material presented above, it is possible to obtain a material based on fly ash which can be used for filling shallow voids and is characterized by the required strength and a relatively short setting time.

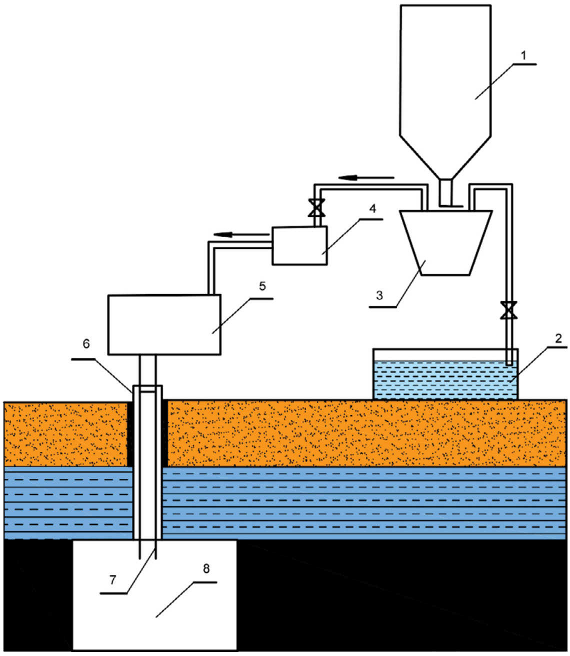

Fig. 2. Liquidation of the void in the rock mass by injection of ash-water mixture according to (Kubański 2008)
1 – ash or cement silo; 2 – water tank; 3 – high-speed mixer; 4 – piston pump; 5 – tank with mixer;
6 – casing pipe; 7 – PVC pipe; 8 – void (shallow excavation)

Rys. 2. Likwidacja pustki w górotworze przez zatłaczanie mieszaniny popiołowo-wodnej

The paper emphasizes the necessity of filling shallow voids in the rock mass in order to eliminate the risk of sinkhole formation.

The objective of the article was to investigate which of the methods applied for the ex post forecast would provide results consistent with the actual state involving the formation of a sinkhole. Then, using these methods, it was determined to what extent the void should be filled so that, in the light of the calculation results, a sinkhole would not develop. The obtained result may be useful in practice in controlling the filling level of the void to prevent the development of a sinkhole. This is important because in practice, it is difficult to fill shallow voids completely due to the existing fracture zones in the rock mass and the spread of the material in large-volume voids.

1. Studied area

The research was conducted within one of the hard-coal mines of the Upper Silesian Coal Basin (Poland). The region is located in the southern part of Poland. The location of the research area is shown in Figure 3.

Fig. 3. Location of the Upper Silesian Coal Basin

Rys. 3. Lokalizacja Górnośląskiego Zagłębia Węglowego

The geological structure of the Basin is presented in a simplified manner in Figure 4. Generally, it can be stated that the rock mass is composed of Paleogene and Neogene layers (clays and sands) and of Triassic layers in some small areas. Under these layers, there are Carboniferous layers with coal seams. The approximate location of the sinkhole is shown in Figure 3.

2. Research method

2.1. Description of the site

In the yard of a detached family house, a cone-shaped sinkhole with an elliptical base, with 3 m and 4 m long axes and a 4 m depth, was formed. The sinkhole appeared at a distance of around 4 m from the building edge. The shape and dimensions of the sinkhole are shown in Figure 5.

Directly under the sinkhole, there was a gallery in a two-meter-thick seam 214. The bottom of the excavation was fifteen meters deep. The gallery was dug at the end of the nineteenth century and built over with wooden supports that probably lost their supportability due to biodegradation, which resulted in the formation of a sinkhole.

The rock mass in the area of the excavation is formed by productive Carboniferous rocks and Quaternary overburden rocks. Sandstone with a thickness of 4.7 m is lying directly

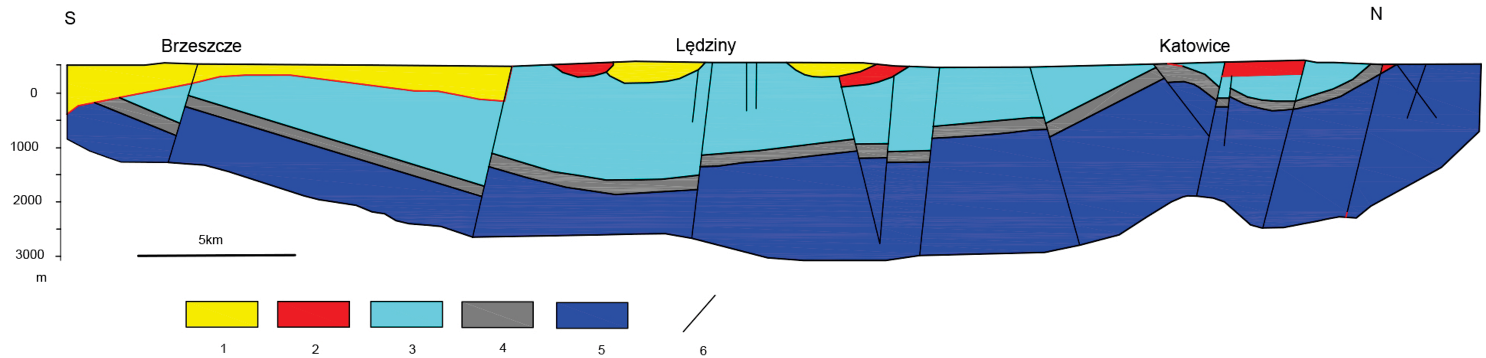

Fig. 4. Geological structure of the USCB according to S. Doktorowicz-Hrebnicki
1 – Palaeogene and Neogene (clays and sands); 2 – Triassic (limestones); 3 – upper Carboniferous (arc group); 4 – upper Carboniferous (saddle group); 5 – upper Carboniferous (marginal group); 6 – tectonic fault

Rys. 4. Budowa geologiczna GZW według S. Doktorowicza-Hrebnickiego

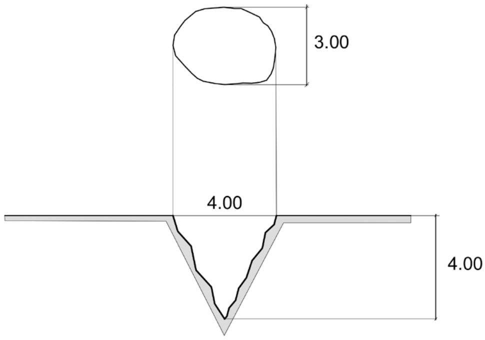

Fig. 5. The shape of the sinkhole

Rys. 5. Kształt zapadliska

above coal seam 214, and above it there is sand with a thickness of 8.3 m, reaching to the surface. The following data was adopted for the calculations – Table 1.

Table 1. Summary of data necessary for calculations

Tabela 1. Zestawienie danych koniecznych do obliczeń

Layer	γ (MN/m^3)	R_r (MPa)	ϕ deg	k_r	h_i (m)
Sand	0.027	0	35	1	8.3
Sandstone	0.025	0.15	30	1.15	4.7
Coal	0.016	0.15	30	1.15	2.0

γ – bulk density in rocks, R_r, – tensile strength, k_r – coefficient of loosening of rocks, h_i – thickness of the layer, ϕ – internal friction angle.
Source: Kidybiński 1982.

In this study, two methods of analyzing the possibility of a sinkhole formation were used:
- an option using the A. Sałustowicz (Sałustowicz 1956) pressure arc theory;
- the M. Chudek – W. Olaszowski method (Chudek et al. 1988).

2.2. Proposed option of using the pressure arc theory to forecast the formation of a sinkhole

The paper by Strzałkowski (Strzałkowski 2015) presents a method of using the pressure arch theory for the purposes of forecasting the creation of sinkholes. According to the above solution, the area of the loose zone P_e is (Figure 6):

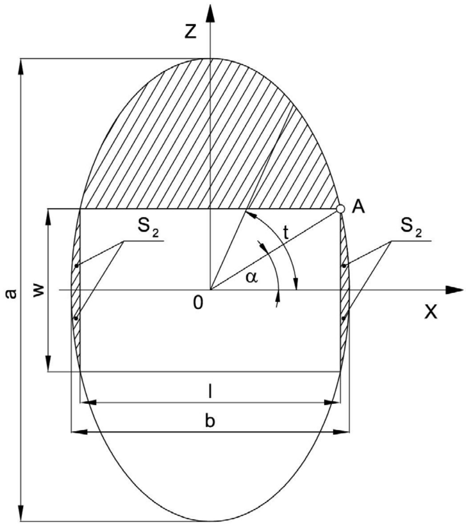

Fig. 6. Loose zone around the void (excavation) in the rock mass (Strzałkowski 2015)

Rys. 6. Strefa odprężona wokół pustki (wyrobiska) w górotworze

$$P_e = S_1 - \frac{wl}{2} + 2 \cdot S_2 = \frac{\pi ab}{8} - \frac{wl}{2} + \frac{2abk - 2wl}{8} = \frac{ab(\pi + 2k) - 6wl}{8} \tag{1}$$

S_1 – the area of the upper half of the ellipse,
w, l – height and width of the excavation.

$$S_2 = \frac{1}{2}\int_0^k \left[\frac{b}{2}\cos t \cdot \frac{a}{2}\cos t - \frac{a}{2}\sin t \cdot \frac{b}{2}(-\sin t) \right] dt - \frac{wl}{8} = \frac{abk - wl}{8} \tag{2}$$

$$k = \frac{\pi\alpha}{180^\circ} \tag{3}$$

$$k = \frac{\pi}{180^\circ} \cdot \arctan\frac{w}{l} \tag{4}$$

According to the work of Strzałkowski (Strzałkowski 2015, 2019), it can be concluded that in the event of a cave in, the rocks of the loose zone undergo displacement towards the void, filling the excavation. Assuming that the area P_1 corresponds to the volume of crushed rock contained in the detensioned zone (hatched area in Figure 6), and the area P_2 corresponds to the volume of the detensioned zone (without rock loosening) and the heading, let us denote:

$$P_1 = P_e \cdot k_r \quad (5)$$
$$P_2 = P_e + w \cdot l$$

k_r – rock loosening coefficient, denoting the ratio of the volume of the same mass of crushed rock to that remaining in the unmined coal.

Two cases can be distinguished:
- when $P_1 = P_2$, the void will backfill, and the rocks contained in the loose zone will fill it tightly,
- when $P_1 < P_2$, in the region of the upper vertex of the loose zone, a secondary void is formed with a volume resulting from the area difference $P_2 - P_1$. When the loose zone associated with it reaches the overburden, a sinkhole is created.

According to the used solution, secondary voids moving towards the surface may be formed, which, when reaching the zone of a loose overburden, cause the formation of a sinkhole on the surface. This descriptive method requires iterative computations, which can be cumbersome at a large number of secondary voids. In order to simplify the calculations, a computer program in C++ is used, which is described in the paper (Strzałkowski 2017). The program has been developed by J. Strzałkowski.

2.3. The M. Chudek – W. Olaszowski method

Using the simplified forecast method, the value of the Z indicator should be calculated first. It is expressed by the formula:

$$Z = \frac{H - h}{w} \quad (6)$$

H – depth of the working's roof, (m),
h – thickness of the loose overburden, (m),
w – height of the working, (m).

The probability of sinkhole formation has been linked to the value of the Z indicator. Its value can be calculated from the formula:

$$P = 0.00019 \cdot Z^2 - 0.036 \cdot Z + 1.34 \quad (7)$$

Naturally, the probability value is within the range <0;1>; therefore, the value of the Z indicator is within the range <10;50>. In the case of $Z < 10$, it should be assumed that $Z = 10$, while if $Z > 50$, then $Z = 50$.

3. Results

Calculations based on the method using the pressure arc theory proposed by P. Strzałkowski

The method presented in Point 3 of this paper was used to perform the analyses. First, calculations were conducted to check whether, using the adopted method, a result indicating the formation of a sinkhole in the case of a void associated with the gallery in seam 214 would be obtained. The data from Table 1 was adopted for the calculations. The following dimensions of the excavation were assumed: 2 m high and 3 m wide.

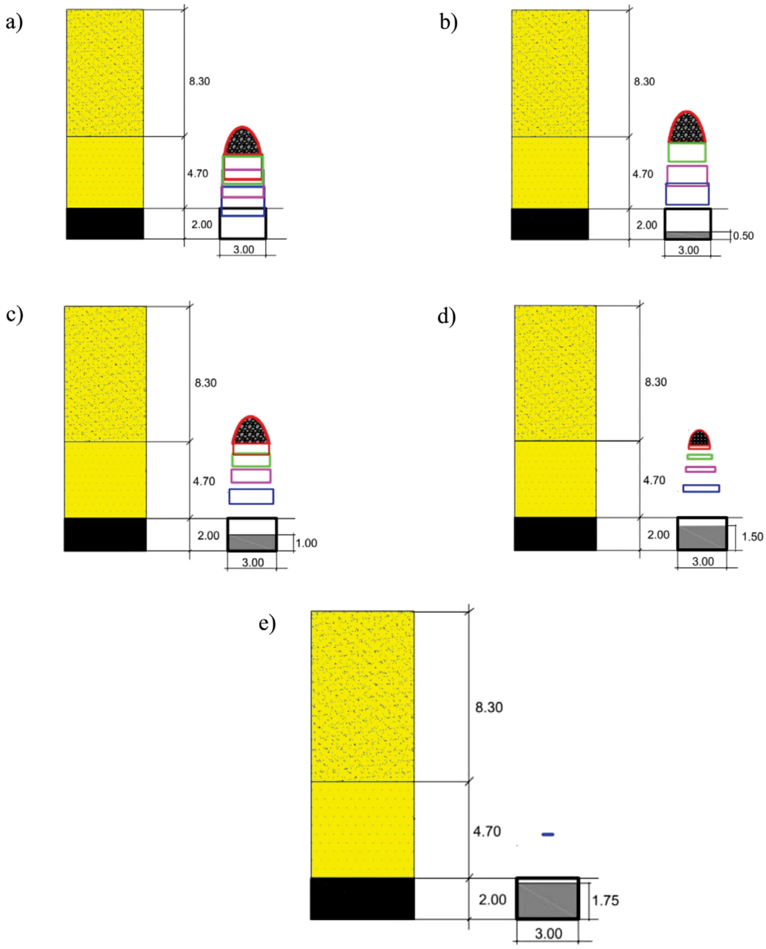

Fig. 7. Graphical interpretation of calculation results
a) an unfilled void; b) a void filled to a height of 0.5 m; c) void filled to a height of 1.0 m;
d) void filled to a height of 1.5 m; e) void filled to a height of 1.75 m

Rys. 7. Graficzna interpretacja wyników obliczeń
a) pustka niewypełniona; b) pustka wypełniona na wysokość 0,5 m; c) pustka wypełniona na wysokość 1,0 m;
d) pustka wypełniona na wysokość 1,5 m; e) pustka wypełniona na wysokość 1,75 m

Due to its low depth and the influence of rainwater and weathering processes, the sandstone was characterized by very low strength, which was taken into account in the calculations – Table 1.

The calculation results obtained by using the described program (Strzałkowski 2017) are graphically presented in Figure 7a. This figure, similar to the following figures, shows the lithological profile of the rock mass and the results of calculations obtained with the use of a computer program in the form of successive secondary voids moving upwards. The first secondary void is marked blue, the second is purple, the third is green, and the fourth is red. The figure shows the stress-relieved zone associated with the last secondary void. As visible, the caving zone of the last of the secondary voids reached the rocks of the loose overburden (sand layer). Therefore, in the light of the results of the calculations, a sinkhole was formed on the surface, which is consistent with the facts.

Subsequently, calculations were performed that assume that the void (excavation) would be filled with the mixture to heights of 0.5, 1.0, 1.5 and 1.75 m. The other assumptions adopted for the calculations have, of course, not changed. It was assumed that the ash-cement-water mixture had a tensile strength not lower than the coal seam. In the light of the literature study presented in this paper, it can be concluded that such a strength is easily achieved, as it can be assumed that the compressive strength is approx. ten times greater than the tensile strength. Figures 7b–e show successive secondary voids and the collapsed zones associated with the last voids. Filling the void to heights of 0.5, 1.0, and 1.5 m does not allow, in the light of the obtained calculation results, avoiding the occurrence of a sinkhole. Only, as it is shown in Figure 7e, in the case of filling the excavation to a height of 1.75 m did the secondary void have very small dimensions: 0.04 m high and 0.53 m wide. This void, located at a depth of 10.9 m, in the light of the calculation results, was filled with loose rocks. Therefore, no sinkhole was formed on the surface.

Thus, in the light of the calculation results, filling the void to a height of 1.75 m eliminated the risk of the formation of a sinkhole on the surface in the analyzed case.

Table 2. The results of calculations performed with the use of the Chudek–Olaszowski method

Tabela 2. Wyniki obliczeń wykonanych metodą Chudka–Olaszowskiego

Z	*w* (m)	P
2.35	2.00	1
3.13	1.50	1
4.7	1.00	1
9.4	0.50	1
18.8	0.25	0.73

Z – indicator in eq. (6); *w* – height of the working; *P* – the probability of the sinkhole formation.

Calculation results using the the M. Chudek – W. Olaszowski method

Following use of the pressure arc theory, calculations were performed using the Chudek–Olaszowski method. The results of these calculations are shown in Table 2. It contains the values of the Z indicator and the probability of a sinkhole formation for the previously adopted working filling heights. As can be seen in the table, the probability of sinkhole formation was lower than 1 ($P < 1$) only when the working was almost completely filled (height of the void 0.25 m). In a sense, consistency with the results of the calculations performed previously was achieved. Of course, complete consistency would occur if the probability value was $P = 0$.

3.1. Discussion of results

The calculations performed with the use of the option based on the pressure arc theory showed the possibility of determining, via subsequent approximations, the height to which the working should be filled in order to avoid the formation of a sinkhole on the surface. The application of the Chudek–Olaszowski method allowed for the determination of the probability of sinkhole formation with a different degree of filling the working – void. In a sense, both methods obtained a similar result. In all cases of filling the working, for which the method based on the pressure arc theory enabled the formation of a sinkhole to be determined, the Chudek–Olaszowski method showed the probability of a sinkhole formation equal to 1. However, in the case when the first of the methods used obtained a result indicating the impossibility of a sinkhole formation, the calculated probability value was lower than 1 and amounted to $P = 0.73$. Of course, with such a high probability value, the area above the void would be treated as having little use for investment due to it being an area endangered by a sinkhole. The formation of a sinkhole in such cases is of course mainly determined by the presence of a shallow void in the rock mass where the loose overburden may be transferred. Therefore, it is important to fill the void with a bonding material that will not move out of the void. Filling shallow voids with loose material that can be washed out does not guarantee the permanent protection of the rock mass against the formation of sinkholes. Consolidated binding material, connected with the surrounding rock, will result in a lack of free space in the rock mass that the loose overburden, washed away by rainwater, would be able to move into.

Conclusions

The information presented in this paper, derived from the literature and as a result of the researchers' own analyses, support the following conclusions:

1. The occurrence of sinkholes in post-mining areas still constitutes a problem, generating a threat to public safety. Especially since sinkholes may occur many years after the shal-

low workings were created and ceased to be used. In the analyzed case, this time was about 100 years.

2. In the opinion of the authors, the most appropriate method of eliminating the risk of the formation of sinkholes is filling shallow voids in the rock mass with water-ash-cement mixtures characterized by a strength selected appropriately to the strength of the rock mass surrounding the void. This material does not move from the working, which prevents the phenomenon of scouring and secures the area against sinkhole formation.
3. An additional ecological advantage of using ash for this purpose is the avoidance of their storage on the surface.
4. The performed calculations indicate the necessity to thoroughly fill shallow voids. In the analyzed case, it was only when the void was filled to 87% of its height that the formation of a sinkhole was eliminated. In the analyzed case, a secondary void was formed, which self-backfilled without generating a sinkhole on the surface.
5. The proposed method of analysis can be used in all geological and mining conditions. It is only essential to know the structure of the rock mass and to have access to the software used in the work. The mechanical properties of rocks can be assumed as being average, based on the literature.

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AN ASSESSMENT OF THE IMPACT OF THE DEGREE OF THE FILLING OF SHALLOW VOIDS ON THE POSSIBILITY OF SINKHOLE FORMATION ON THE SURFACE

Keywords

sinkhole, elimination of sinkhole threat

Abstract

The issues covered by the work are important and topical as sinkholes that develop in large numbers over shallow mining excavations pose a great threat to public safety. In Upper Silesia (Poland), the formation of sinkholes can be observed even for a period of over 100 years following the termination of mining works. An effective method of risk elimination consists of filling the voids with a binding material with strength properties similar to those of the rocks surrounding the void. The application of fly ash is very suitable for this purpose, the use of which also has an ecological aspect. The literature studies presented in the paper indicate the possibility of making mixtures with the use of fly ash that has the required strength parameters. The compressive strength of the mixtures after solidification is up to 3 MPa, or even up to 7 MPa, and in some cases, up to 15 MPa. Most of the voids at shallow depths are found in coal seams, in which the compressive strength at shallow depths amounts to approx. 5 MPa. Thus, by filling the void with such material, we can ensure conditions similar to those prevailing before the excavation was made. The paper presents a case study involving the formation of a sinkhole above a dog heading and an ex post forecast made with the use of two selected methods. These methods yielded results affirming that the development of a sinkhole in the considered conditions is certain. Then, using the said methods, the impact of the filling level of the void on the possibility of sinkhole development was analyzed. The obtained results indicated the necessity to fill the void to around 90% with the use of one of the methods and its complete filling with the use of the other method.

OCENA WPŁYWU STOPNIA WYPEŁNIENIA PŁYTKICH PUSTEK NA MOŻLIWOŚĆ POWSTANIA ZAPADLISKA NA POWIERZCHNI

Słowa kluczowe

zapadlisko, likwidacja zagrożenia zapadliskiem.

Streszczenie

Zagadnienia, których dotyczy praca, są ważne i aktualne, gdyż zapadliska licznie powstające nad płytkimi wyrobiskami górniczymi stanowią duże zagrożenie dla bezpieczeństwa publicznego. Na Górnym Śląsku (Polska) powstawanie zapadlisk obserwuje się nawet przez okres ponad 100 lat od zaprzestania prowadzenia robót górniczych. Skuteczną formą likwidacji zagrożenia jest wypełnianie pustek materiałem wiążącym o własnościach wytrzymałościowych zbliżonych do własności skał otaczających pustkę. Znakomicie do tego celu nadają się popioły lotne, których wykorzystanie posiada również aspekt proekologiczny. Studia literaturowe przedstawione w pracy wskazują na możliwość tworzenia mieszanin z udziałem popiołów lotnych o wymaganych parametrach wytrzymałościowych. Wytrzymałość na ściskanie mieszanin po zestaleniu wynosi do 3 MPa, a nawet do 7 MPa, a w niektórych przypadkach do 15 MPa. Większość pustek na małych głębokościach występuje w pokładach węgla, którego wytrzymałość na ściskanie wynosi około 5 MPa na małych głębokościach. Zatem wypełniając takim materiałem pustkę, można zapewnić warunki zbliżone do tych, jakie panowały przed wykonaniem wyrobiska. W pracy przedstawiono studium przypadku powstania zapadliska nad wyrobiskiem korytarzowym i wykonano prognozę ex post przy zastosowaniu dwóch wybranych metod. Metody te pozwoliły na uzyskanie wyników mówiących o pewności powstania zapadliska w rozpatrywanych warunkach. W dalszej kolejności analizowano przy ich zastosowaniu wpływ stopnia wypełnienia pustki na możliwość powstania zapadliska. Uzyskane wyniki wskazały na konieczność wypełnienia pustki w około 90% przy zastosowaniu jednej z metod i całkowitego jej wypełnienia przy zastosowaniu drugiej z metod.