Assessment of the hazard level posed to a post-mining area by discontinuous surface deformations

M Chudek and P Strzałkowski
Silesian University of Technology, Faculty of Mining and Geology, 2 Akademicka Street, 44-100 Gliwice, Poland
E-mail: piotr.strzalkowski@polsl.pl

Abstract: This paper is a case study of assessment of hazard level posed to a post-mining area by the possible occurrence of sink holes. Detailed analyses pertaining to the above are often hindered due to the incompleteness of geological and mining documentations prepared in the 19th and the beginning of the 20th century. Among other methods, the assessments were conducted using solutions developed by the authors. The issues addressed in the paper are of the highest significance due to the necessity to ensure public safety in the areas of former, shallow mining exploitation in the Upper Silesia, where cases of sink holes over shallow workings are noted each year.

1. Introduction
Over two hundred years of coal mining in Upper Silesia caused a wide spectrum of surface transformations. Irrespective of the geological and mining conditions, the mining exploitation always causes the occurrence of continuous deformations [1, 2, 3]. These deformations may be relatively easily anticipated using one of the many available methods. Discontinuous deformations are those in which the terrain continuity is visibly broken. Such deformations may exist in the following forms: the linear and the surface deformations. The most frequently observed form of linear deformations is a step in ground, connected with mining extraction led in a few coal seams to the same border, especially in the vicinity of tectonic faults. The most common form of surface type deformations are sinkholes. The methods of sinkhole predictions have been presented in the paper [4]. Discontinuous surface deformations – with sink holes being a dominant form – are more difficult to predict. Their formation is often random and is related to the collapse of shallow voids at depths from 80 to 100 m in the Upper-Silesian Coal Basin. The voids are often a result of former mining headings, especially shafts and roadways. In the papers [1, 2, 3, 4, 5, 6, 7], numerous examples of formation of sink holes have been provided, which unequivocally exhibits the fact that the problem of anticipating the possibility of their formation remains valid. A wide range of forecasting methods of discontinuous surface deformations has been presented in papers [1, 2, 3, 4, 5, 6, 7]. Forecasting the formation of sink holes is often hindered by the uncertainty of data. Shallow headings are related to mining works conducted a long time ago, which results in the fact that adequate mining and geological documentation is often not available or incomplete. Old workings were often left as they were or liquidated in a manner which did not guarantee the safety of the surface. The documentation of the methods of their liquidation is also rarely available. Alongside the so-called bootleg mining conducted without any documentation, this exhibits the magnitude of difficulties encountered while assessing the possibility of formation of sink holes. This situation is reflected in the criteria of usability of post-mining areas for construction,
presented in the paper [8]. As it has been shown in table 1 below, cited from the paper referred to above, the assessment of usability of such areas is not based on the forecasts of deformations, but only based on the fact of former shallow exploitation, presence of non-liquidated shafts and the former occurrence of discontinuous deformations. Another thing is that it is difficult to prepare detailed analyses encompassing the entire mining area of a given coal mine, including the prognoses of sink-holes. Such analyses may, however, be prepared for smaller areas, as exemplified by the case study presented within this paper.

**Table 1.** Categories of mining areas of liquidated mines due to construction limitations [8].

| Cat. | Level of post-exploitation transformation | Limitations in use for construction | Hazards | Notes |
|------|-------------------------------------------|-----------------------------------|---------|-------|
| A    | little transformed                         | useful area (if bearing soils are present and the water table is below 2 m) | not present in practice | To eliminate small damages to structural and finishing elements, considering a reinforcement of the structure is advised |
| B<sub>1</sub> | continuous deformations at subsidence not causing flooding | | The area may be classified as A after 5 years from completing the exploitation. |
| B<sub>2</sub> | transformed | conditionally useful | low B<sub>2,1</sub> <sup>1)</sup> Discontinueous transformations with a hazard level: | medium B<sub>2,2</sub> <sup>2)</sup> high B<sub>2,3</sub> <sup>3)</sup> | In case of shallow exploitation of useful minerals and borehole exploitation of sulphur as well as the presence of shafts causing a hazard classified as B2,1 and B2,3, it is possible to make the land useful for construction by backfilling the voids or using special foundation methods. In areas with B2,3 hazard level, C classification should be considered, depending on the risk analysis. |
| B<sub>3</sub> | gas | | | |
| C    | highly transformed                         | unfit area | overflows and floodings, areas with landslide hazards and large-area sinkholes (including hazard zones around non-liquidated shafts) | | It is advised to exclude construction in areas of non-liquidated shafts, borehole exploitation, protective strips around opencast mining areas, waste heaps including protective zones – use of area in a manner different than construction (green areas, recreation, etc.) |

Notes: 1), 2), 3) for table 1 [8]:

1) When all the conditions mentioned below have been fulfilled:
   - no sinkholes,
   - no suffusion phenomena,
   - surface-connected vertical and dip headings with known liquidation methods,
   - thickness of firm roof rocks at least five times the height of mining headings.
2) When at least one of the conditions mentioned below has been fulfilled:
   - presence of sink holes with a diameter not exceeding 3 m,
   - presence of ledges,
   - presence of fissures,
   - presence of shafts and small shafts with unknown liquidation methods,
   - thickness of firm roof rocks not exceeding five times the height of mining headings and exceeding three times the height of mining headings,
   - horizontal and dip headings with unknown liquidation methods.

3) When at least one of the conditions mentioned below has been fulfilled:
   - presence of sink holes with a diameter exceeding 3 m,
   - presence of ledges,
   - presence of fissures,
   - presence of suffusion phenomena,
   - thickness of firm roof rocks not exceeding three times the height of mining headings,
   - presence of bootleg mining workings,
   - presence of fire phenomena in areas of shallow coal exploitation,
   - Presence of intensive paraseismic phenomena.

2. Study case. Analysis of geological and mining conditions

2.1. Morphology and land development
The relief of the area in concern is not very diversified and its height in relation to the sea level is approx. 302 m. In the plot, shaft “A” was driven at the end of the 19th century and buildings were raised (hoisting machine and shaft top buildings as well as an administrative building). The buildings were demolished in the 60s of the former century. Currently the area is idle and intended for development – figure 1.

![Figure 1](image_url)

**Figure 1.** General view of the area of the liquidated shaft “A”. 
2.2. Lithology and stratigraphy
In the area in concern, the rock mass structure may be determined based on the lithological profile of shaft A. The overburden is constituted by diluvial Quaternary strata in the form of sandy loam with a thickness of 2.5 m. Below the diluvium, Carboniferous saddle beds are found in the form of interchanging shales and sandstones accompanying the 500 coal seam. The lithological profile of shaft “A” has been shown in figure 2.

2.3. Tectonics
No tectonic disturbances have been found in the direct vicinity of shaft “A”.

Figure 2. Lithological profile of shaft “A”. 1 – sandy loam, 2 – soft sandstone, 3 – soft shale 4 – inflammable shale, 5 – fine - grained shale, 6 – shale, 7 – coal, 8 - sandstone, 9 – coal, 10 – sandstone.
2.4. General characteristics of the mining works
For obvious reasons, no mining exploitation was conducted in the direct vicinity of the shaft. There is, however, a series of intersecting workings, most likely made using wooden props. A gallery in the seam 510 was led directly from the shaft (a very rare development heading). Headings exhibited in figure 3 have been driven in the area of the shaft. Headings near the shaft have been driven at a depth of 63.70 m and the shallowest is at the depth of 59.38 m – figure 3. The information whether the headings have been liquidated is not available. Based on the authors’ experience, the probable dimensions of the galleries were assumed: the height of 2.5 m and width of 3 m.

Shaft “A”, with a diameter of 4.8 m, was liquidated in 1965. The liquidation of the shaft consisted in building a platform at a depth of 13 m from the surface, backfilling the top section using barren rock and covering the shaft with a concrete plate. In the years 1965 and 1968, mine gases were emitted through fissures in the rock mass by the shaft “A”.

![Figure 3](image)

**Figure 3.** The system of galleries by the shaft A. 1 – sandstone, 2 – coal seam.

3. The applied sink hole forecasting methods

3.1. The M. Chudek – W. Olaszowski method
This method is one of the most commonly applied in the conditions of the Upper Silesian Basin and was described in the works [1, 2, 3, 4]. Due to this, only the most significant information concerning this method has been provided.

The authors have assumed that two zones are formed over the void after self-backfilling: The caving zone and the cracking zone – figure 4.

The height of the caving zone is determined by the following formula:

\[
\begin{align*}
    w_c &= g \frac{4(k + 1) - \pi(k - 1)}{2\pi(k - 1)} \\
    (1)
\end{align*}
\]

where:
- \( w_c \) – the maximal height of the caving zone,
- \( k \) – loosening coefficient of the rocks in the caving zone,
- \( g \) – height of the primary void (working).
The fulfilment of the following inequality is a condition sufficient for the sink hole to form:

\[ w_z \geq H - h \]  

(2)

where:

\( H \) – depth of the working in relation to the roof,
\( h \) – thickness of the overburden.

The height of the cracking zone is determined by the following formula:

\[ w_s = \pm M \sqrt{\frac{(L + g \cdot tg \alpha)^2 (M^2tg^2\alpha + 1)}{4(1-M^2tg^2\alpha)}} - \frac{g}{2} \]  

(3)

where:

\( L \) – width of the void (exploitation heading),
\( \phi \) – internal friction angle,
\( M = a/b \),
\( a \) – vertical axis of the pressure ellipse,
\( b \) – horizontal axis of the pressure ellipse.

**Figure 4.** Outline of the caving and cracking zones over the void according to [4].

In cases where the cracking zone reaches the rocks of the loose overburden, the sink hole may, but does not have to be formed.

In practice, it is very convenient to use a simplified forecasting method, consisting in the calculation of the \( Z \) indicator. The indicator corresponds to a probability \( P \) of formation of a sink hole that may be read from a table or calculated using a polynomial. The indicator is expressed by the following formula:

\[ Z = \frac{H - h}{g} \]  

(4)
3.2. *The method based on the A. Sałustowicz pressure arch theory*

The applied method [10, 11] is based on the pressure arch theory developed by A. Sałustowicz [9]. According to the author, the pressure arch is formed around a working when the following condition is fulfilled: \( \sigma_{\text{max}} \geq R_r \), namely, when the stresses in the working in the x direction - \( \sigma_x \), are not smaller than the tensile strength of the rocks - \( R_r \). Otherwise, the working remains in a stable state.

In the paper [10], the results of calculations were presented, while departing from the simplified assumptions made by the pressure arch theory author. The area of the stress-relieved zone \( P_e \) (crosshatched in figure 5) is:

\[
P_e = S_1 - \frac{wl}{2} + 2 \cdot S_2
\]

where:

- \( S_1 \) – area of the top half of the cracking ellipse (stress-relieved zone), \( S_1 = \frac{\pi ab}{8} \)
- \( w, l \) – height and width of the working

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

- \( k \) – arc measure of the \( \alpha \) angle, thus \( k = \frac{\pi \alpha}{180^\circ} = \frac{\pi}{180^\circ} \cdot \arctan \frac{w}{l} \)

Thus:

\[
P_e = \frac{ab(\pi + 2k) - 6wl}{8} \tag{6}
\]

*Figure 5. Stress-relieved zone around the void (working) in the rock mass [12].*
In case of the fall of the roof, the rocks contained in the stress-relieved zone move towards the void and fill the working. The following designations of auxiliary variables have been assumed:

\[ P_1 = P_e \cdot k_r, \]
\[ P_2 = P_e + w \cdot l \]

\[ \text{(7)} \]

where:

- \( k_r \) – coefficient of loosening of rocks.
- Other designations as in previous formulas.

In practice, two cases may occur:

- if \( P_1 = P_2 \), a self-backfilling of the void will occur and the rocks contained in the stress-relieved zone will fill it tightly,
- if \( P_1 < P_2 \), a secondary void will be formed in the area of the top of the stress-relieved zone, with a volume resulting from the difference in the \( P_2 - P_1 \) areas. If the related stress-relieved zone will reach the overburden, a sink hole will be formed.

To facilitate the calculations, a computer program was developed in C++ programming language (author: J. Strzałkowski), presented in paper [11], which calculates using the iterative method. A simplification was applied, consisting in the assumption that subsequent voids were approximated to a rectangular shape while maintaining the proportions (ratio of side lengths) characteristic to the working (the primary void).

A method of determining the zone affected by the sink hole formed due to the loss of stability of a shaft [12]. The dimensions of the sink hole hazard zone are determined by the formula [12] – figure 6:

\[ D = 2 \cdot Z \cdot \tan(90^\circ - \varphi) + 2r \]

\[ \text{(8)} \]

where:

- \( h \) – the thickness of the loose overburden,
- \( \varphi \) – mean internal friction angle of the loose overburden material,
- \( r \) – radius of the shaft working.

\[ \text{Figure 6. The diameter of the sink hole that may be formed due to the loss of stability of the shaft according to [12]. 1 – loose overburden, 2 – strong rock mass, 3 – shaft.} \]
4. Calculation results
The following parameter values characterizing the rock mass were assumed for the calculations [1, 2, 13]:

- Sandy loam: bulk density $\gamma = 0.027 \text{ MN/m}^3$, tensile strength $R_r = 0.02 \text{ MPa}$, loosening coefficient $k_r = 1$, internal friction angle $\phi = 20^\circ$.
- Shales: bulk density $\gamma = 0.025 \text{ MN/m}^3$, tensile strength $R_r = 1.5 \text{ MPa}$, loosening coefficient $k_r = 1.2$
- Sandstones: bulk density $\gamma = 0.025 \text{ MN/m}^3$, tensile strength $R_r = 2.0 \text{ MPa}$, loosening coefficient $k_r = 1.2$
- Coal: bulk density $\gamma = 0.014 \text{ MN/m}^3$, tensile strength $R_r = 0.6 \text{ MPa}$, loosening coefficient $k_r = 1.2$

The calculations were made for the workings with the following dimensions: height of 2.5 m and width of 3.0 m, located at the floor levels of: 63.70 m – working I and the shallowest working, 59.38 m – working II.

Calculation results according to the M. Chudek – W. Olaszowski method:
For both the workings the height of $w = 2.5 \text{ m}$ and the loose rocks overburden of $h = 2.5 \text{ m}$ were assumed.

- Working I
  - Caving zone height – $W_c = 16.3 \text{ m}$
  - Z indicator = 23.48
  - Probability of sink hole formation $P = 0.60$

- Working II
  - Caving zone height – $W_c = 16.3 \text{ m}$
  - Z indicator = 21.75
  - Probability of sink hole formation $P = 0.65$

Thus, in both cases in consideration, the caving zone will not reach the rocks of the loose overburden, while it may be reached by the cracking zone.

**Figure 7.** The primary and secondary voids. Calculations according to the method based on the pressure arch theory. 1 – The last void, 2 – The excavation (mining pit).
Calculation results according to the method based on the pressure arch theory
The results of calculations were obtained using the computer program described in paper [11].

Working I
The primary void will transform into a caving zone and subsequent secondary voids will move towards the surface. The last secondary void will reach the sandstone stratum over the coal seam and its floor will be located at the depth of 60 m. The dimensions of the void will be: height: 1.7 m, width: 2.1 m. A pressure arch will not be formed over the void and thus the sink hole will not be formed – figure 7.

Working II
The ratio of the axes of the cracking ellipse is negative ($n = -1.3$). No pressure arch will be formed over the void and thus the working will not become a caving zone. This means that the sink hole may not be formed.

The diameter of the sink hole that may be formed due to the loss of stability of the shaft according to the formula (8): $D = 23.3$ m.

5. Summary and conclusions
The hazard posed to the areas of former, liquidated (especially many years ago) mines by the formation of discontinuous surface deformations remains a valid problem. As the paper [8] exhibits, while determining the usability of areas for development, the geological and mining conditions related to the historical shallow exploitation should be considered. In the opinion of the authors of the paper, in case of relatively small areas, one may and should conduct more detailed analyses than advised in [8], aimed at the assessment of the hazard level of formation of sink holes. This is of significance due to the small area of the lands where investments may be planned in the Upper-Silesian Coal Basin. The area in concern may be classified as B2,3 or even C (unfit for construction). The detailed analyses conducted within the study indicate as follows:

1. The probability of formation of sink holes over the galleries, as provided by the M. Chudek and W. Olaszowski method, is approx. 0.6. However the emission of mine gases from rock mass at the location of “A” shaft suggests that cracking zone reaches loose overburden. According to the results of calculations based on the pressure arch method, the sink holes will not be formed. Considering, however, the high variability of strength parameters of rocks and the possible decrease thereof due to the low depth, one should consider the risk of a sink hole formation, nonetheless. In this case, geophysical survey ranging to a depth of approx. 60 m (which is difficult) should be conducted, alongside boreholes. Shall any possible voids be identified, they should be liquidated. A correctly conducted liquidation of voids, the effectiveness of which would be verified by surveys, would allow for the safe use of the area.

2. It should be accepted that the method of liquidation of shaft A does not ensure the stability of the subsoil. The area subject to the hazard of sink hole formation alongside an additional safety zone should be excluded from development or the liquidation of the shaft should be performed in line with the developed guidelines [14].

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