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CIVIL ENGINEERING

Contribution to the a priori assessment of the value of the caving zone expansion coefficient in the forecast of ground surface uplift caused by the flooding of closed coal mines in the Ruhr region/Germany

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Abstract. The article presents a methodology for determining the value of the expansion coefficient of a reconsolidated caving zone in the context of forecasting the rise in underground mine water levels and consequent surface subsidence caused by the process of flooding the closed coal mines. The paper also provides a brief characterisation of analytical predictive models regarding surface subsidence during the process of flooding coal mines. In order to describe the vertical deformation of the reconsolidated porous rock mass in the caving zone, a linear-elastic medium of Biot was utilised. The conducted theoretical calculations demonstrate a high agreement with the results obtained through the identification of the expansion coefficient parameter based on the analysis of in-situ subsidence measurements in Dutch and German mining areas. The proposed methodology was applied to a real case study involving the forecasting of the impact of the flooding process on the underground workings of the German Ibbenbüren mine. The article constitutes a significant contribution to the field of forecasting the rise in underground mine water levels and surface subsidence during the process of flooding closed coal mines. The presented methodology and obtained results can be valuable for researchers, engineers, and decision-makers involved in the planning and management of mining areas.

Keywords: uplift; caving zone; closed mine; flooding; subsidence.

1. INTRODUCTION

After the completion of mining operations, the coal mines located in the central part of the Ruhr region will be flooded to a level of −600 meters above sea level. This boundary is due to the need to protect the drinking water resources located above the Carboniferous layers in the surrounding rock formation, among other reasons.

After the drainage pumps are turned off, the process of flooding occurs naturally through the influx of water from the surrounding rock formation, leading to a gradual rise in the level of mine water [1–3]. As evidenced by field experiments and in situ measurements, this process leads relatively quickly to ground surface uplift movements [4–10]. According to the legal regulations in Germany, the documentation for the closure of a mining facility (known as a "mine") must include a forecast of ground deformations caused by the flooding process in order to assess the risk to the surface area and the objects located there [11].

Among the analytical methods widely used in Germany for predicting ground uplift, the methods developed by Pöttgens, Fenk, and Sroka should be mentioned [5, 12, 13]. These methods assume that the increase in pressure in the pores of the consolidated infarct zone, caused by the rise in the mine water level, leads to the vertical expansion of this zone and is the direct cause of the observed surface uplift. The central parameter in these methods is the so-called coefficient of expansibility of the consolidated infarct zone located in the roof area of the exploited mining fields.

2. ANALYTICAL MODELS FOR PREDICTING GROUND SURFACE UPLIFT IN THE PROCESS OF FLOODING CLOSED COAL MINES

The proposed analytical solutions by Pöttgens [5] and Sroka [13] are based on a finite element of the consolidated rock rubble in the caved zone of the exploited deposit, combined with a selected influence function (transforming function) equation (1):

$$h(r,t) = \varphi(r) \cdot \Delta V(t), \tag{1}$$

where:
$h(r,t)$ – distribution of uplift on the surface at time t caused by the flooding of the consolidated caved zone element,
r – horizontal distance of the calculation point from the caved zone element,

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$\varphi(r)$ – influence function (transforming function),
$\Delta V(t)$ – increase in the volume of the consolidated caved zone element due to flooding.

This relationship is schematically presented in Fig. 1.

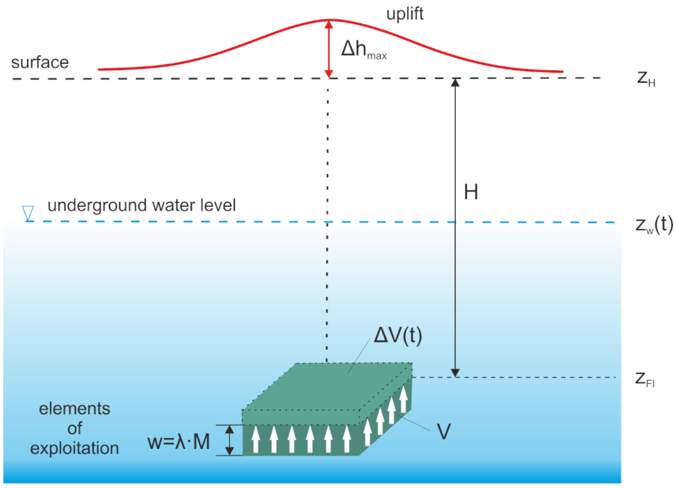

Fig. 1. Graphic representation of the mathematical model of uplift caused by mine flooding (based on [13])

The increase in the volume of the caved zone element is calculated using equation (2):

$$\Delta V(t) = d_m \cdot \Delta p(t) \cdot V, \tag{2}$$

where

$$\Delta p(t) = (z_w(t) - z_{Fl}) \cdot \gamma_w, \tag{3}$$

$$V = \Delta x^2 \cdot w = \Delta x^2 \cdot \lambda \cdot M. \tag{4}$$

In equations (2), (3), and (4), the symbols have the following meanings:

d_m – coefficient of expansion of the consolidated caved zone element,
$\Delta p(t)$ – increase in vertical pressure in the caved zone caused by the rise in mine water level at time t,
V – volume of the caved zone element,
Δx – dimension of the square base of the caved zone element,
w – absolute height of the caved zone ($w = \lambda \cdot M$),
M – thickness of the exploited coal seam,
λ – relative height of the caved zone (typically $2 \leq \lambda \leq 4$), depending on the type of overlying rocks,
$z_w(t)$ – water level at time t,
z_{Fl} – height of the flooded caved zone element,
γ_w – specific weight of water [MPa/m].

In the solution proposed by Pöttgens [5], the influence function is identical to Geertsma's theoretical solution [14] for surface subsidence calculations in gas reservoir exploitation (equation (5)):

$$\varphi(r, H) = \frac{1-\nu}{\pi} \cdot \frac{H}{(r^2 + H^2)^{3/2}}, \tag{5}$$

where:
ν – Poisson's ratio,
H – depth of the infarct zone element.

On the other hand, Sroka's solution [13] is based on the influence function given by Knothe [15] for subsidence calculations in underground coal mining (equation (6) [16]:

$$\varphi(r, R_w) = \frac{1}{R_w^2} \exp\left(-\pi \frac{x^2}{R_w^2}\right), \tag{6}$$

where:

$$R_w = H \cdot cot\beta_w.$$

The angle β_w limits the horizontal range of uplift. Its value depends on the properties of the surrounding rock mass, and for the conditions in the Ruhr Basin, it is typically around 12° [6].

The solutions presented by Pöttgens [5] and Sroka [13] pertain to a single element of the caved zone. Assuming that the caved zone surfaces resulting from mining are identical to the surfaces of the exploited parts of the coal seam in one or multiple layers, the total uplift value at any surface point can be calculated using the principle of linear superposition by summing up elemental uplifts. In Sroka's method [13], the dimension of the square base of the caved zone element should not exceed $\Delta x < 0.1R_w$.

Fenk's approach [12] differs fundamentally from the solutions provided by Pöttgens and Sroka. According to Fenk, the expected uplift values at surface points due to the rise in mine water level are proportional to the subsidence values caused by previous mining activities. This relationship can be expressed as equation (7):

$$h_i(t) = B(t) \cdot s_i, \tag{7}$$

where:
$h_i(t)$ – uplift value at the i-th point at time t,
s_i – subsidence value at the i-th point caused by previous mining activities,
$B(t)$ – functional-coefficient.

The functional coefficient $B(t)$ is described by the theoretical solution given by Fenk as:

$$B(t) = d_m \cdot \Delta p(t) \left[\frac{E_s}{\gamma_G \cdot H} - 1\right], \tag{8}$$

where:
E_s – stiffness modulus of the consolidated rock mass in the caved zone,
γ_G – average specific weight of the rock in the consolidated caved zone.

Fenk's method is primarily applied to single-seam mining. Furthermore, as indicated by in-situ uplift measurements, the horizontal range of uplift caused by the rise in mine water level is significantly greater than the range of subsidence. This raises doubts about Fenk's assumption of a proportional relationship between uplift and subsidence.

3. THE COEFFICIENT OF EXPANSION d_m OF THE CONSOLIDATED CAVED ZONE

The mining of coal seams using the longwall method with a caved roof leads to the formation of a chaotic goaf zone above the mined-out area, with a height of approximately 2 to 4 times the thickness of the extracted seam [5,17,18]. Under the pressure determined by the mining depth and over time, by analysing the behaviour of rocks in this zone, three characteristic phases can be distinguished: the caving phase, the goaf reinforcement phase, and the long-term reconsolidation phase. The first two phases, in the case of longwall mining, typically last relatively short, from a few days to a maximum of a few weeks. The third phase, as indicated by in situ subsidence measurements conducted on the surface, can last even several decades after the completion of mining operations [10, 19–21].

When the decision is made to initiate the process of flooding closed mines by ceasing water pumping, all goaf zones located above the mining fields in the extracted coal seams are in the long-term reconsolidation phase. Assuming that the behaviour of the compressed porous rock mass in the goaf zone can be described as linearly elastic according to Biot's theory [22, 23], the value of the coefficient of expansion of the goaf zone d_m can be expressed using equation (9):

$$d_m = \frac{\alpha(\eta)}{E_s}, \tag{9}$$

where:

α – the Biot's coefficient, whose value depends on the type of rock material in the goaf zone and the average value of open porosity in this zone [24],

η – the open porosity of the consolidated goaf zone.

The value of the expansion coefficient d_m corresponds to the value of the vertical tensile strain of the consolidated goaf rock mass for an increase in pore pressure by one unit.

The open porosity of the compressed rock goaf zone above the extracted seam average can be calculated by using the subsidence coefficient a. This coefficient describes the relationship between the subsidence trough volume M_z on the surface and the volume of the extracted deposit V_z, equation (10):

$$a = \frac{M_z}{V_z}. \tag{10}$$

Based on analyses conducted using in situ subsidence measurement results, the value of this coefficient for longwall mining with a caved roof primarily depends on the mining depth. For mines in the Ruhr region, it was found that this relationship can be described using a regression formula [25], equation (11):

$$a(H) = 1 - \exp(-\xi \cdot H), \tag{11}$$

where:

$$\xi = 0.248 \cdot 10^{-2} \pm 0.032 \cdot 10^{-2} \; \left[m^{-1}\right]$$

and

$$600 \le H \le 1250 \text{ m}$$

The value of the subsidence coefficient increases with the mining depth H, which is related to the increasing pressure of the surrounding rock mass in the caved zone. This pressure also leads to faster reconsolidation of the goaf area. Equation (11) was derived from the analysis of subsidence measurement results for up to 1.0 to 1.5 years after the completion of mining operations.

The difference, equation (12)

$$\Delta a_0 = 1 - a \tag{12}$$

describes the volume losses in the rock mass as the subsidence trough passes through the rock mass. According to [26], these losses occur almost exclusively in the caved zone.

Assuming that the relative height of the caved zone λ concerning the thickness of the extracted seam is given, we obtain the formula for the average value of the open porosity of the consolidated caved zone, equation (13):

$$\eta = \frac{\Delta a_0}{\lambda + \Delta a_0}, \tag{13}$$

or approximately, equation (14):

$$\eta = \frac{1 - a}{\lambda}. \tag{14}$$

The value of the Biot's coefficient for the consolidated rock in the caved zone can be calculated using a regression formula given by Gustkiewicz [22], or alternatively by Fabre and Gustkiewicz [23], equation (15):

$$\alpha(\eta) = 1 - \exp\left(-\mu \cdot \tan\left(\eta \cdot \frac{\pi}{2}\right)\right). \tag{15}$$

According to Gustkiewicz [22], the average value of the coefficient μ for the studied rocks (granodiorite, granite, slate, sandstone) is:

$$\overline{\mu} = 3.5934.$$

Detailed laboratory test results for limestone and sandstone lead to the following conclusions [23]:

- for limestone: $\mu = 4.1 \pm 0.2$,
- for sandstone: $\mu = 5.5 \pm 1.5$.

According to the plan of RAG AG, for the protection of groundwater resources above the Carboniferous layers, mines located in the central part of the Ruhr region will be flooded to a level of -600 m above sea level. The average depth of the extracted coal seams below this level is approximately 900 m. Using equation (11), we obtain that the average value of the subsidence coefficient, approximately 1.0 to 1.5 years after the completion of mining operations, is:

$$a = 1 - \exp\left(-0.248 \cdot 10^{-2} \cdot 900\right) = 0.8927.$$

This result is confirmed by regularly conducted identifications of the subsidence coefficient parameter based on in situ subsidence measurements. Assuming $\lambda = 3$, this leads to the average value of the open porosity, equation (13):

$$\eta = 0.0345,$$

which is equivalent to 3.45%.

This value of porosity gradually decreases over time after the completion of mining operations until the start of the flooding process, as demonstrated by long-term observations of in situ subsidence.

According to Gustkiewicz's empirical formula [22], the corresponding value of Biot's coefficient is equation (16):

$$\alpha = 1 - \exp\left(-3.5934 \cdot \tan\left(0.0345 \cdot \frac{\pi}{2}\right)\right) = 0.1771. \tag{16}$$

According to studies by various authors, the value of the elastic modulus of reconsolidated sandstone rock in the caved zone lies between 45 and 56 MN/m^2 (Table 1).

Table 1

The value of the modulus of stiffness of consolidated sandstone rocks in the caved zone

Author	Coal basin	E_s [MN/m^2]
Fenk [12]	Zwickau	46.6
	Freital	56.0
Tunger [27], Zhao *et al.* [8]	Bannewitz/Freital	45.9

Assuming an average value of $E_s = 49.5$ MN/m^2 for further calculations, the value of the expansion coefficient d_m is obtained as:

$$d_m = \frac{0.1771}{49.5} = 0.3571 \cdot 10^{-2}\ \text{m}^2/\text{MN}.$$

This corresponds adequately to the values obtained through the parameter identification method by analysing the results of in-situ uplift caused by the rise in the mine water level (Table 2).

Table 2

The value of the modulus of stiffness d_m of consolidated sandstone rocks in the caved zone

No	Author	d_m [m^2/MN]	λ	ϵ [m^2/MN]
1	Pöttgens [5] Südlimburger Revier/Netherlands	$0.35 \cdot 10^{-2}$	4	$1.40 \cdot 10^{-2}$
2	Goerke-Mallet [18] Ibbenbüren/Germany	$0.46 \cdot 10^{-2}$	3	$1.38 \cdot 10^{-2}$
3	Sroka, Preusse [6] Aachener Revier/Germany	$0.353 \cdot 10^{-2}$	3	$1.06 \cdot 10^{-2}$
4	Tunger [27] Bannewitz/ Germany	$0.480 \cdot 10^{-2}$	3	$1.44 \cdot 10^{-2}$
5	Preusse, Sroka [28] Königsborn-Ruhr Revier/Germany	$0.364 \cdot 10^{-2}$	3	$1.09 \cdot 10^{-2}$

It should be noted that there is generally difficulty in accurately assessing the relative height of the caved zone above the mined coal seam. As the values of d_m and λ are multiplicative quantities in the given mathematical models, Sroka and Preusse [6] proposed the concept of an integrated uplift coefficient, which is the product of both quantities, equation (17):

$$\epsilon = d_m \cdot \lambda. \tag{17}$$

The comparative calculations for three values of the relative height of the caved zone λ (between 2 and 4) and the characteristic roof conditions in the Ruhr Coalfield are presented in Table 3.

Table 3

Values of the expansion coefficient d_m and integrated uplift coefficient ϵ for three values of the relative height of the caved zone λ

λ	1	2	3
porosity η	0.0476 (4.76%)	0.0323 (3.23%)	0.0244 (2.44%)
Biot coefficient α	0.3378	0.2434	0.1901
expansion coefficient d_m	$0.676 \cdot 10^{-2}$	$0.487 \cdot 10^{-2}$	$0.380 \cdot 10^{-2}$
integrated uplift coefficient ϵ	$1.352 \cdot 10^{-2}$	$1.461 \cdot 10^{-2}$	$1.520 \cdot 10^{-2}$

The results in Table 3 were obtained using the following data:

- post-mining exploitation coefficient: $a = 0.9$,
- sandstone roof: $\mu = 5.5$,
- modulus of stiffness for the consolidated sandstone rock: $E_s = 50$ MN/m^2.

Measurements of ground surface subsidence after the end of mining operations indicate that the reconsolidation process of the caved zone can last for several decades [19, 20, 29]. Therefore, the permeability porosity of the reconsolidated caved zone decreases over time. By analysing the long-term subsidence behaviour, the volume loss in the caved zone can be described analogously using the formula, equation (18):

$$\Delta a(t) = \Delta a_0 \cdot \exp(-c \cdot \Delta t), \tag{18}$$

where:

Δa_0 – relative volume loss at the time of mining termination,

Δt – time after mining ends,

c – average value of the time coefficient indirectly describing the relative subsidence behaviour after mining termination.

This leads to the average porosity value $\eta(t)$ given by equation (19):

$$\eta(t) = \frac{\Delta a(t)}{\lambda + \Delta a(t)}. \tag{19}$$

The calculated results of the expansion coefficient dm and the integrated uplift coefficient ϵ are presented in Table 4, assuming that the flooding process will commence approximately 5 years after mining termination and with a value of the time coefficient parameter $c = 0.1$ year^{-1}. These results confirm the findings of research conducted by Tunger [27], which indicate that a delayed onset of the flooding process significantly reduces the value of the expansion coefficient, as it is caused by the continuous and long-lasting reconsolidation process, resulting in a gradual decrease in the open porosity of the caved zone.

Table 4
Computational results for $\Delta t = 5$ years

λ	1	2	3
porosity η	0.0294 (2.94%)	0.0198 (1.98%)	0.0149 (1.49%)
Biot coefficient α	0.2247	0.1574	0.1211
expansion coefficient d_m	$0.449 \cdot 10^{-2}$	$0.315 \cdot 10^{-2}$	$0.242 \cdot 10^{-2}$
integrated uplift coefficient ϵ	$0.898 \cdot 10^{-2}$	$0.945 \cdot 10^{-2}$	$0.968 \cdot 10^{-2}$

4. EXAMPLE CALCULATION – IBBENBÜREN

As part of the closure activities of the Ibbenbüren coal mine in Germany, predictive calculations were performed for uplift caused by the rise in the mine water level in the eastern field (Ostfeld) of the mine [30]. The calculations were conducted using Sroka's geometric-integral model [13]. Mining operations in the Ibbenbüren eastern field were conducted from 1800 to 2018, involving the extraction of coal from 22 seams at depths ranging from 45 to 1570 metres. According to the closure documentation, it was assumed that the maximum water level in the mine would not go beyond +65 metres above sea level.

The following values for data and parameters of the calculation method were adopted for the predictive calculations:

- average ground surface elevation: $z_T = +160$ m a.s.l.,
- final mine water level elevation: $z_w = +65$ m a.s.l.,
- expansion coefficient of the caved zone: $d_m = 0.40 \cdot 10^{-2}$ m^2/MN,
- relative height of the caved zone: $\lambda = 3$,
- integrated uplift coefficient: $\epsilon = 1.20 \cdot 10^{-2}$ m^2/MN,
- angle of influence during uplift: $\beta_w = 12°$.

The results of the uplift calculations caused by the rise in mine water level in the Ibbenbüren eastern field are presented in Fig. 2. The maximum predicted uplift value is 38 cm. The maximum calculated values for slope (T) and horizontal strain (ε) for the protection of surface structures are as follows:

$T_{\max} = 0.13$ mm/m,
$\varepsilon^{+}_{\max} = 0.17$ mm/m,
$\varepsilon^{-}_{\min} = -0.07$ mm/m.

These values are significantly below the magnitude that would be expected to cause damage to surface structures.

5. CONCLUSIONS

The article presents the results of studies related to determining the a priori value of the expansion coefficient of the consolidated caved zone in the process of flooding closed coal mines. The solution assumes that the vertical deformation of the consolidated

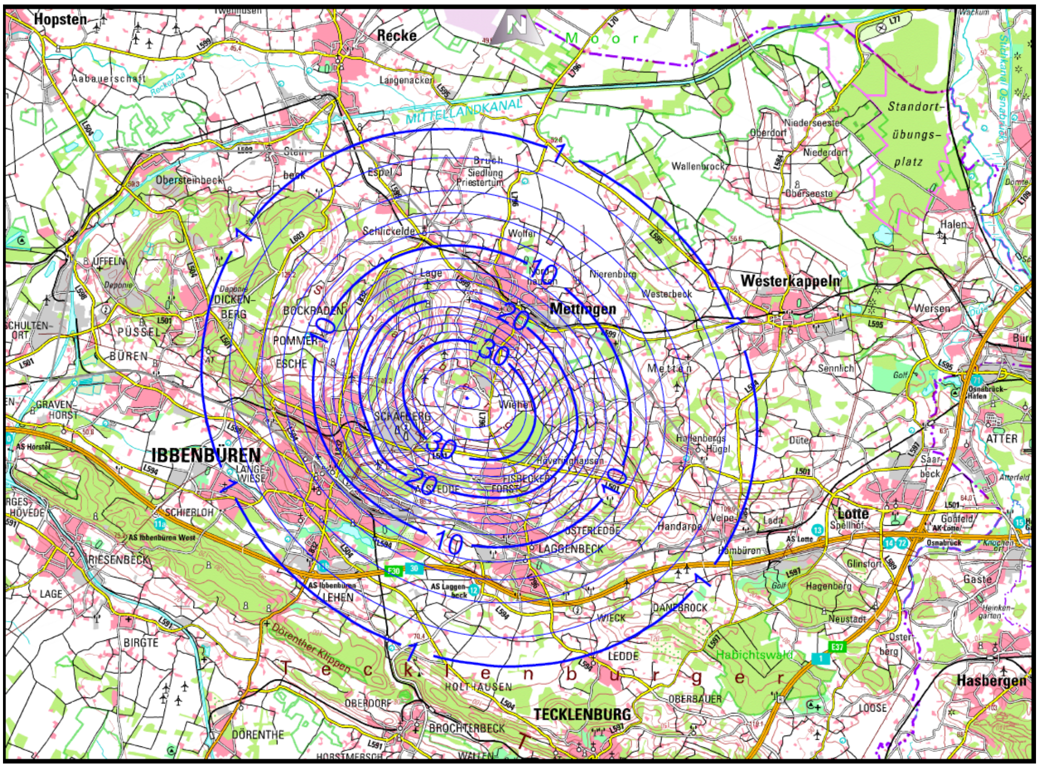

Fig. 2. Forecast of uplift (in cm) for the Ibbenbüren eastern field

porous rock mass in the caved zone caused by pore pressure increase can be described using the linear-elastic Biot medium.

The conducted theoretical calculations show a high agreement with the results obtained through the identification of the expansion coefficient parameter based on the analysis of in situ uplift data from Dutch and German mining regions.

The proposed methodology was applied to a real-world example, namely the prediction of the impact of the flooding process on the underground workings of the Ibbenbüren mine. The results indicate small values of the maximum slope (T) and horizontal strain (ε).

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