Evaluation the strength and sealing capability of boundary pillars in coal mines

Adam Frolik

Central Mining Institute, pl. Gwarków 1, 40-166 Katowice, Poland (e-mail: bhxaf@gig.katowice.pl.)

Abstract: The objective of the evaluation of boundary pillars is to analyze the strength and leak tightness of the abandoned rock body performing a function of the barrier for minewaters inflowing from a flooded mine. The methods based on the rock tensile and/or shear strength as well as the methods based on the pillars displacement and crush are taken into account while evaluating the stability of boundary pillars. The analysis of the permeability of boundary pillars performing a function of groundwater barriers is based on theoretical assumptions that the one–dimensional infiltration is subject to Darcy's Law and takes into account the rock mass infiltration parameters and the underground water reservoir pressure values. Such an evaluation analysis can yield the following parameters:

– barrier pillar geometrical dimensions;
– rock physicomechanical properties of the pillar;
– reservoir hydraulic and pillar water infiltration parameters.

1 INTRODUCTION

The barrier pillar is the rock body abandoned between the water hazard source and the active mine opening and the purpose of which is to prevent groundwater and saturated loose material from inrushing into the opening threatening the people working there and interrupting the mine production continuity. Polish mining regulations require that, before the start of mining operations in the vicinity of gob aquifers, first of all, the minewaters be drained and only when there is no such an eventuality the barrier pillars be determined. However, the guidelines regarding the barrier pillar determination are lacking. In this case, the mining companies, most often, either abstain from operations in the vicinity of aquifers or undertake mining operations when the aquifer is dewatered or closed. As a result of the recent efforts made in the direction of closing a number of mines, the pillar problem has again come into consideration, for fear that the actions undertaken to stop pumping out water and the resulting impoundments of water in abandoned mines can bring about excessive inflows or inrushes of minewater through the boundary pillars creating hazard for the active mine drainage systems.

2 THE BARRIER PILLAR STRENGTH

The barrier pillars separating the hazardous aquifer from the operating underground mine section should be located in competent and coherent and washout-resistant rocks. Depending on the locations of the water hazard source and the operating mine section, the following safe barrier pillars can be distinguished:

- cross-measure or vertical ones ($D_{p.}$) as, for example, those under the flooded gobs;
- parallel to bedding or horizontal ones (D_r), i.e. those located in a coal body of the same seam as that in which an aquifer is located (Figure 1).

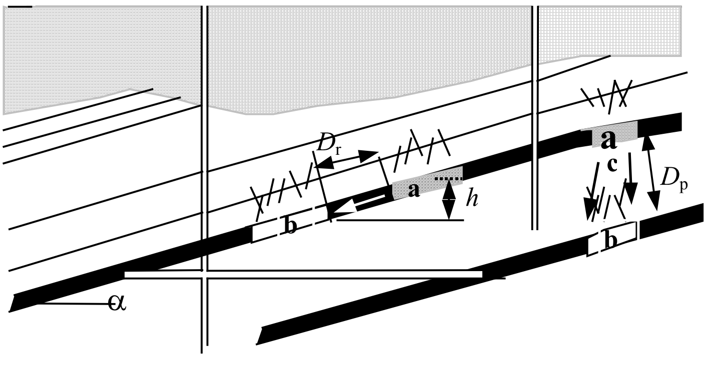

Figure 1 Illustration of the active workings under minewater inflow hazard from gob aquifers. *(a) Flooded old workings; (b) Active mine working; (c) Crack pattern in the roof of a working. Arrows indicate possible minewater inflow paths from old workings into a new, active working.*

The most widely used methods for the evaluation of safe barrier pillars are as follows:

- Slesariev's method (Kamieński et al., 1956), (Konstantynowicz et al., 1974). The width of the pillar can be derived from the pillar tensile strength.
- A method based on the pillar shear strength (Krajewski, 1957).
- A method based on the pillar displacement strength (Labasse, 1962).
- A method based on the pillar crushing strength (Rogoż, 1987/1).
- A method based on the rock workability coefficient derived from the modified GIG method (Kidybiński, 1982).

To estimate the existing stress and/or pillar stability values, the knowledge of the following rock geotechnical parameters is required:

- γ, bulk density;
- R_c, compressive strength;
- R_r, tensile strength;
- shear parameters: ϕ, internal friction angle; c, cohesion;
- f, workability index.

The approximate value of the workability index f can be calculated from the formula

$$f = 0{,}36\sqrt{R_c}$$

where R_c = compressive strength (MPa).
Table 1 shows the average values and intervals of the mechanical parameters characterizing the Upper Silesian Coal Basin Carboniferous rocks, that have resulted from the many years of studies carried out by the Central Mining Institute (Kidybiński, 1982).

Table 1 Geotechnical properties of the Upper Silesian Coal Basin Carboniferous rocks

No.	Type of rocks	R_c, MPa	R_r, MPa	ϕ, °	c, MPa	γ, kN/m³
1.	Coarse-grained sandstones	$\frac{48}{9 \div 96}$	$\frac{4,6}{2,8 \div 10,8}$	33÷5	$\frac{16}{2,5 \div 20}$	24.7
2.	Siltstones and medium-grained sandstones	$\frac{70}{10 \div 165}$	$\frac{6,0}{3,5 \div 10,8}$	30÷32		24.8
3.	Mudstones	$\frac{50}{9 \div 107}$	$\frac{3,7}{2,0 \div 8,1}$	26÷29	$\frac{10,0}{1,0 \div 15,0}$	24.6
4.	Claystones	$\frac{35}{7 \div 62}$	$\frac{2,8}{1,8 \div 6,2}$	23÷27		24.8
5.	Hard coal	$\frac{16}{4 \div 46}$	$\frac{0,8}{0,4 \div 1,7}$	21÷24	$\frac{4,5}{0,5 \div 8,0}$	13.0

It should be noted that the above mentioned values refer to the geotechnical parameters determined at laboratories on small rock samples mostly devoid of weakness surfaces. However, the rock strength R_m in massif is much lower than the rock strength R_o temporarily measured on a small sample at a laboratory. Considering the appropriate weakness coefficients, the rock strength in massif can be determined from the formula (Kidybiński, 1982)

$$R_m = R_o \cdot k_1 \cdot k_2 \cdot k_3$$

where k_1 is the strength scaling coefficient equal to 0.33 for sandstones; 0.42 for mudstones and 0.55 for claystones;
k_2 is the weakness time coefficient for long-term loading (>100 days) equal to 0.5 for coal; 0.6 for mudstones and claystones and 0.7 for sandstones;
k_3 is the weakness moisture coefficient that ranges from 0.5 to 1.0 for the majority of rocks depending on the rock saturation degree.

Multiplying the above coefficient yields the general coefficient in the form

$$\xi = k_1 \cdot k_2 \cdot k_3$$

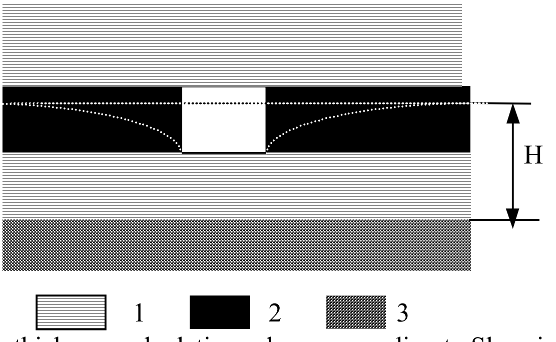

Figure 2 Safe barrier thickness calculation scheme according to Slesariev
1 - Impermeable coal seam roof and floor rocks 2 - Coal seam 3 – Aquifer

Its commonly used value is ξ = 0.1. The strength of the massif markedly decreases due to the existence of weakness surfaces and, therefore, the value of ξ for the mining disturbed ground can even be equal to 0.003.
In the case of Polish mines, the Slesariev's method based on the tensile strength has mostly been used in the evaluation of barrier pillars (Kamieński et al., 1956).
The formulas for the safe barrier critical dimension *D* (width or thickness) are as follows:

$$D = \frac{e^2}{2\eta \cdot R_r}\left(\gamma + \sqrt{\gamma^2 + \frac{4\eta \cdot R_r}{e^2}(\gamma_1 \cdot h_1 + p)}\right) \tag{1}$$

for overlying perch aquifers:

$$D = \frac{e^2}{2\eta \cdot R_r}\left(\sqrt{\gamma^2 + \frac{4\eta \cdot R_r}{e^2}p} - \gamma\right) \tag{2}$$

for underlying aquifers:

$$D = e\sqrt{\frac{p}{\eta \cdot R_r}} \tag{3}$$

for lateral groundwater inflow;
where p = permissible hydrostatic pressure in an aquifer, kPa;
η = a constant of a barrier pillar equal to 1.33 for varying strata deposition and 2.0 for stable strata deposition;
R_r = strata's temporary tensile strength, kPa;
γ = bulk density of barrier pillar strata, kN/m^3;
γ_1 = bulk density of loose water bearing formations (quicksand), kN/m^3;
h_1 = thickness of loose water bearing formations overlying the barrier pillar, m;
e = span of an opening, m:

$$e = \frac{a \cdot l}{a + l} \quad \text{for entries,}$$

$$e = \frac{b \cdot l}{0{,}5 \cdot l + b} \quad \text{for longwall coalfaces with hydraulic backfilling;}$$

a = width of an entry, m;

l = width of a longwall coalface, or length of an entry segment unsupported or temporarily supported, m;

b = maximum distance between the longwall coalface and the backfilling, m.

By considering a significant decrease in coal tensile strength arising from structural weakening of coal in massif $R_r = R_{r\,śr}/8$ (Kidybiński, 1982) and by assuming the permissible stress value with a safety factor equal to 2 instead of the tensile strength, the formulas for the barrier pillar width can be obtained.
The Slesariev's equation incorporating the dip α of a coal seam can be expressed in the form:

$$D = \frac{e^2}{2\,\eta \cdot R_r}\left(\pm\gamma \cdot \sin\alpha + \sqrt{\gamma^2 \sin^2\alpha + \frac{4\eta \cdot R_r \cdot p}{e^2}}\right) \tag{4}$$

By considering that $\eta = 1.33$, $\gamma = 13$ kN/m^3 (bulk density of coal) and $e = 2\,g$ and after replacing R_r with k_R and by using appropriate conversion factors in order to express pressure in MPa units, the formula for the minimum dimensions of a safe barrier pillar can be given as

$$D = D_r = g\sqrt{60 \cdot p + 0{,}15 g^2 \sin^2\alpha} \pm 0{,}4 g^2 \sin\alpha\,, \tag{5}$$

where (+) and (-) are used when the aquifer is located updip above the active workings and downdip beneath the active workings, respectively.
When the angle of dip of a coal seam is less than 15° or when the active workings are located adjacent to an aquifer (along the coal seam strike), the equation 5, after the reduction rearrangement, can be expressed in the form

$$D = D_r = g\sqrt{60 \cdot p}\,, \tag{6}$$

where g = coal seam mining thickness or the entry's cross-sectional dimension, m;

p = aquifer's water pressure, MPa;

α = angle of dip of a coal seam, °;

$g^{(r)}$ = coal seam thickness, appropriate for calculation, defined as $g^{(r)} = g \cdot \varpi$

ϖ = filling compressibility factor assumed to be equal to 1.0 for caved in area, 0.5 for solid stowing and 0.2 for hydraulic filling.

The general formula for the safe barrier width and thickness as used by the method that takes into account the ground's shear strength (Krajewski, 1957) can be expressed in the form

$$D = \frac{p \cdot a \cdot c}{2 \cdot k_t (a + c) \pm a \cdot c \cdot \gamma \cdot \cos\alpha} \tag{7}$$

where a = width of entry, m;
b = height of entry, m;
$c = b/\sin\alpha$
p = hydrostatic pressure, MPa;
k_t = permissible shear stress, MPa;
p = aquifer's water pressure, MPa;
γ = bulk density of rocks, MN/m^3;

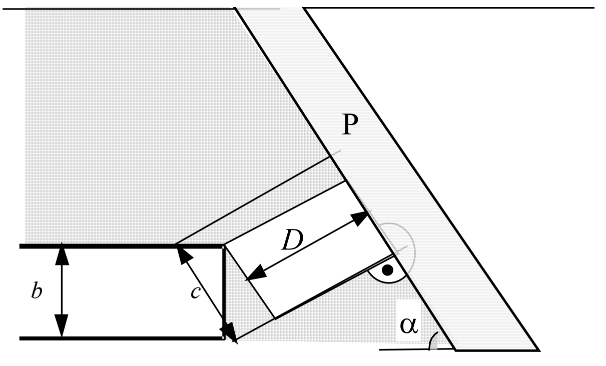

Figure 3 Minimum safety distance against minewater inflows

Depending on the location of an opening relative to the water hazard source, the formula can be rearranged to obtain the following modified forms:

- if the entry approaches an aquifer located beyond a vertical interface (α=90°) as, for instance, the water bearing fault, then c=b and

$$D = \frac{p \cdot a \cdot b}{2 \cdot k_t (a + b)} \tag{8}$$

- if the entry is driven under the aquifer (α=0°), then

$$D = \frac{p \cdot a}{2 \cdot k_t - a \cdot \gamma} \tag{9}$$

- if the entry is driven parallel to the aquifer, then

$$D = \frac{p \cdot b}{2 \cdot k_t} \tag{10}$$

The results obtained from the formulas (7) through (10), owing to the ground structural weakening, should be multiplied by the safety factor K=1.5 to 2.0.

Labasse (1962) developed a method for calculating widths of the safe barriers against the inflows from flooded cavities. In the method, it has been assumed that the coal seam roof and floor frictional resistances are the forces preventing the barrier failures. The condition of equilibrium can be in the form

$$2\gamma \cdot H(\cos\alpha + \frac{1-\sin\varphi}{1+\sin\varphi}\sin\alpha)(D-a-a')f \geq K(\gamma_w \cdot M \cdot h\, \mu\, \gamma \cdot M \cdot D \cdot \sin\alpha) \quad (11)$$

where H = depth of coal seam at the location of barrier pillar, m;
γ = bulk density of rocks, kN/m^3;
ϕ = angle of internal friction between coal and waste rock;
h = water table level in old workings above the coal seam floor at the bottom of a barrier pillar, m;
f = coefficient of friction;
α = angle of dip of coal seam, °;
K = safety factor higher than unity;
M = thickness of coal seam, m;
γ_w = specific gravity of water, γ_w=10 kN/m^3;
a, a' = widths of destressed zones measured in meters from the sides of flooded gobs and active workings, respectively.

After introducing the values ϕ=37° and f=0.2 and after properly rearranging that expression, the formula defining the minimum width of a safe barrier can be written as

$$D = \frac{K \cdot M \cdot h \cdot \gamma_w + 0{,}4H \cdot \gamma(\cos\alpha + 0{,}25\sin\alpha)(a+a')}{0{,}4H \cdot \gamma(\cos\alpha + 0{,}25\sin\alpha)\, \mu\, K \cdot \gamma \cdot M \cdot \sin\alpha} \quad (12)$$

In formulas (11) and (12), the signs "+" and "-" denote the aquifers underlying and overlying (in the updip direction) the active workings, respectively.
To evaluate the overburden load related crushing strength of a safe barrier pillar; the following formula for the calculation of protecting pillar widths for passageways can be used:

$$D = \sqrt{\frac{H \cdot (2{,}5 + 0{,}6 \cdot M)}{f}} \quad (13)$$

where H = depth of mining, m;
M = coal seam mining thickness, m;
f = workability index obtained by using the modified method developed in the Central Mining Institute (Kidybiński, 1982).

The barrier pillars smaller than 20 m have not practically been applied to Polish mines (Rogoż, 1987/1).

3 EVALUATING THE BARRIER PILLAR SEALING CAPABILITY

The analysis of the groundwater flow through safe barrier pillars is based on the theoretical assumptions that water infiltrates the rock body which performs a function of a barrier pillar. In the analysis, the barrier pillar geometry and infiltration parameters as well as the values of aquifer hydraulic pressure are taken into account (Figure 4.).

Figure 4 Schematic diagram of water infiltration flow through a pillar

The groundwater infiltration flux through the safe barrier pillar located between an active excavation and an aquifer in old workings can be assumed to be the one-dimensional infiltration and calculated according to the Darcy's Law expressed in the following form:

$$Q = 60 \cdot k \cdot L \cdot M \frac{H-h}{D} \tag{14}$$

where Q= infiltration flux, m^3/min;

k = Darcy`s coefficient for barrier pillar rock mass (coal), m/s;

L, D = length and width of the barrier pillar where the infiltration process takes place, m;

M = thickness of a selected coal seam on both sides of the barrier pillar, m;

H = water head in old workings, m;

h = ordinate of protected excavation floor, m.

The length L of the barrier pillar should be estimated based on the map of mine workings. The values of M, h and D are considered to be the average ones, which is dictated by the linearity of Darcy's Law.

While calculating the barrier pillar infiltration possibility, the determination of the most likely value of Darcy`s coefficient for the coal barrier can present the most of difficulties. Some investigations into the coal's water infiltration property carried out in situ for degasification of coal seams produced results ranging from $8{\cdot}10^{-9}$ to $5{\cdot}10^{-7}$m/s. The laboratory determined Darcy`s coefficient for coal has been ranging from $1.5{\cdot}10^{-7}$ to $3.45{\cdot}10^{-6}$m/s. However, the latter results could be overestimated due to the destressing and damage of coal samples after their extraction from deposit (Frolik, 1998). The results of Darcy`s coefficient investigations not only for coal but also for the other Carboniferous rocks have shown that, practically, no rocks of the Darcy`s coefficient values higher than $5{\cdot}10^{-6}$m/s would be found. For the majority of cases, considering a value of $5{\cdot}10^{-6}$m/s for Darcy`s coefficient k of barrier pillars, yields overestimated values of the infiltrations flux and, thus, gives some margin of safety. The water-filled fissures can also occur in a rock mass and can, under particular conditions, be washed out. Such conditions, however, mainly, occur in the Łaziskie and Libiąskie sandstone beds.

The verification of Darcy`s coefficient values for the coal barrier pillar located between an active excavation and an aquifer in old workings can be done based on hydraulic calculations of the data obtained from the measurement of water seepage from the barrier. The calculations made for the barrier pillars of the Kazimierz-Juliusz and Niwka-Modrzejów coal mines (Frolik, 1998) yielded results ranging from $2{\cdot}10^{-8}$ to $2.9{\cdot}10^{-6}$m/s, the values contained within the bounds determined for coal by both the laboratory and field methods.

The Darcy`s coefficient k for the mining disturbed coal barrier pillar of the Staszic coal mine has been found to be even of a value of $1.2\cdot10^{-5}$m/s. In this case, the full reconsolidation of a coal seam has not taken place despite a great pressure arising from the overlying overburden strata. It follows from the mining practice that the barrier pillar strength with such a high value of Darcy`s coefficient is still out of being under hazard. However, if higher values of Darcy`s coefficient and very liable to erosion strata occur, the probability of the barrier pillar failure significantly increases.

Once the "drawer" type boundary pillars between the mines occur, the vertical groundwater infiltration through the crack system overlying caving areas between the gobs located in two coal seams lying one over the other can take place. Thus, it will be assumed that the infiltration process can take place not only in the positive deformation zones, i.e. along the underlying coal seam mining edges, but on the total surface of superimposed gobs. Considering that the water head above the underlying coal seam is equal to the distance between the coal seams, the groundwater infiltration flux can be given by (Rogoż, 1987/2)

$$Q = 60 \cdot A \cdot f(\frac{z}{g}) \qquad (15)$$

where A = surface of superimposed gobs of both coal seams, m^2;
z = distance between coal seams, m;
g = thickness of underlying coal seam, m,

and the function $f(\frac{z}{g})$ can define changes in groundwater conductivity of a caving zone. The function can be expressed in the form

$$f(\frac{z}{g}) = 0{,}0024 \cdot e^{-0{,}3465 \cdot \frac{z}{g}}$$

4 CONCLUSIONS

The safe barrier pillar is the rock body abandoned between the water hazard source and the active mine opening and the purpose of which is to prevent groundwater and saturated loose material from inrushing into the opening threatening the people working there and interrupting the mine production continuity. To evaluate the bearing capacity of boundary pillars being under load of water pressure in flooded workings, the following methods can be used:

- Slesariev's method which is applied to calculating the pillar's width from its breaking strength. The width is directly proportional to the square root of the aquifer water pressure.
- Krajewski's method which considers the pillar's shear strength. The pillar's dimensions depend on both the vertical load and the water pressure.
- The method which considers the pillar's crushing strength where the rock workability coefficient is determined from the modified GIG method.

The active mine workings would become threatened by the flooded abandoned mine workings if the boundary pillars were excessively infiltrated by minewater. The Darcy`s coefficient values for coal can significantly be scattered, so the minewater inflow through the boundary pillars will not precisely be evaluated using these infiltration rates. For the majority of cases of evaluating the amounts of water infiltrating the safe barrier pillars it could be enough to assume a value of $5 \cdot 10^{-6}$m/s for Darcy`s coefficient k, which allows overestimating the infiltration flux and, thus, obtaining some margin of safety.

Investigations into real groundwater safe barrier pillars have shown that higher values of coal permeability must be expected in the case of the coal pillars disturbed by mining operations in underlying coal seams. In such cases the complete reconsolidation of a coal seam performing a function of a barrier pillar will not always be achieved despite high pressures associated with the load of overlying strata. The impermeability of the pillar could be ineffective forever.

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Ocena filarów granicznych pod kątem możliwości przejęcia przez nie funkcji przeciwwodnych filarów bezpieczeństwa

Adam Frolik

Streszczenie: Ocena filarów granicznych sprowadza się do analizy wytrzymałości i szczelności pozostawionej calizny skalnej, stanowiącej barierę dla przepływu wód z zatopionej kopalni. Przy ocenie stateczności filarów granicznych , uwzględnia się metody wyprowadzane z wytrzymałości skał na rozciąganie lub ścinanie, oraz metody przyjmujące możliwość przesunięcia filara

bądź jego rozgniecenie. Analizę przepływu przez filary graniczne, przejmujące przeciwwodnych filarów bezpieczeństwa, opiera się na założeniach teoretycznych filtracji jednowymiarowej podlegającej prawu Darcy'ego, z uwzględnieniem parametrów filtracyjnych calizny skalnej i wielkości ciśnienia charakteryzującego zbiornik podziemny. Uwzględnia się przy tym parametry calizny skalnej, uzyskane w oparciu o analizę rzeczywistych parametrów hydraulicznych i wielkości przepływów przez istniejące filary przeciwwodne.