The possibility of increasing the efficiency of accessible coal deposits by optimizing dimensions of protective pillars or the scope of exploitation

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Abstract. One of the ways to protect objects exposed to the influences of mining exploitation is establishing protective pillars for them. Properly determined pillar provides effective protection of the object for which it was established. Determining correct dimensions of a pillar requires taking into account contradictory requirements. Protection measures against the excessive influences of mining exploitation require designing the largest possible pillars, whereas economic requirements suggest a maximum reduction of the size of resources left in the pillar. This paper presents algorithms and programs developed for determining optimal dimensions of protective pillars for surface objects and shafts. The issue of designing a protective pillar was treated as a nonlinear programming task. The objective function are the resources left in a pillar while nonlinear limitations are the deformation values evoked by the mining exploitation. Resources in the pillar may be weighted e.g. by calorific value or by the inverse of output costs. The possibility of designing pillars of any polygon shape was taken into account. Because of the applied exploitation technologies the rectangular pillar shape should be considered more advantageous than the oval one, though it does not ensure the minimization of resources left in a pillar. In this article there is also presented a different approach to the design of protective pillars, which instead of fixing the pillar boundaries in subsequent seams, the length of longwall panels of the designed mining exploitation is limited in a way that ensures the effective protection of an object while maximizing the extraction ratio of the deposit.

1. Introduction
The essential way of protecting important objects exposed to mining exploitation is designing the protective pillars. Exploitation of a deposit in the protective pillar, basically acceptable, requires special conditions, such as selection of the appropriate method of roof control, an adequate time coordination of exploitation fronts, abandonment of the exploitation of some seams and an appropriate objects’ protection. It is also important to develop an accurate forecast of the influences of mining exploitation, based on one of the newest methods [e.g. 1]. It should be noted however that establishing protective pillars is not a flaw-free way of protecting objects. Leaving an unextracted part of seam entails a number of negative effects, both in rock mass and on the terrain surface. These include: the increase of the stresses value and risk of high-energy shocks and bumps in the part of deposit located within the pillar as well as formation of a relative upheaval on the terrain surface.
It is very important to design properly the boundaries of a protective pillar in individual seams. A pillar that is too small not only fails to protect the object but can even worsen its maintenance conditions in comparison with mining out of the deposit occurring under the object. On the other hand, a protective pillar that is too large (in terms of ensuring that the permissible deformation values are not exceeded) causes a deterioration of economic results of a mine due to higher operating costs of hampered mining (inside the pillar) compared to the off-pillar exploitation.

Over the last few decades the method of determining pillars in coal mines has undergone some changes, which were introduced in the published instructions. Older Instructions were put into mandatory application by the regulations of Minister of Mining and Energy (Instructions no. 19 of 1961, Directive no. 4 of 1986).

The latest instruction for determining protective pillars, developed in Central Mining Institute [2], provides two ways of determining protective pillars:

- in a manner similar to the Instruction of 1961, the pillar’s boundaries are determined in individual seams based on the angles of range of permissible exploitation influences. The size of this angle depends on the resistance category of an object (or objects).
- with the use of a simplified analytical method that ensures that the object or objects are fully protected from the occurrence of deformations that exceed permissible values. This method consists in the determination of pillar radiuses based on geological and mining data, basic parameters of the theory and specific criterion indicators of deformation that characterize resistance of the protected object.

The guidelines also allowed the determination of a protective pillar on the grounds of an expert opinion based on other justified assumptions. The solutions presented in this article fit in the above, expert way of designing the boundaries of a protective pillar.

2. Determining the boundaries of the protective pillar (the scope of exploitation) as the solution of a certain nonlinear programming task

Designing of the protective pillar (the lengths of longwall panels) was treated as a nonlinear programming task [3]. Solving it demands searching for the minimum of the objective function \( F_c \):

\[
F_c = \sum_{i=1}^{n} w_i g_i P_i
\]  

(1)

with limitations:

- for surface objects:
  \[
  \sum_{i=1}^{n} \varepsilon(R_i) \leq \varepsilon_{dop}
  \]  
  (2)
  \[
  \sum_{i=1}^{n} T(R_i) \leq T_{dop}
  \]  
  (3)
  \[
  \sum_{i=1}^{n} K(R_i) \leq K_{dop}
  \]  
  (4)
  \[
  R_{i\text{grn}} \leq R_i \leq R_{i\text{maks}}
  \]  
  (5)

- for shafts (pits):
  \[
  \max |\sum_{i=1}^{n} \varepsilon z(R_i)| \leq \varepsilon_{z\text{dop}}
  \]  
  (6)
  \[
  R_{i\text{min}} \leq R_i \leq R_{i\text{maks}}
  \]  
  (7)

Additionally, in the case of determining optimal dimensions of protective pillars, it is possible to introduce an additional limitation of the form:

\[
R_{i+1} \geq R_i \quad \text{for} \quad i = 1, \ldots, n - 1
\]  

(8)

In the case of optimization of the lengths of longwall panels this limitation looks as follows:

\[
R_i \geq R_j \quad \text{for} \quad i, j \in \{1, \ldots, n\}
\]  

(9)

where:

- \( n \) – number of seams (or longwalls which panel length is subject to optimization),
- \( w_i \) – weight of the \( i \)-th seam (the \( i \)-th longwall),
- \( g_i \) – thickness of the \( i \)-th seam (height of the \( i \)-th longwall),
$P_i$ – surface area of the pillar in the $i$-th seam, (surface area of unextracted part of the $i$-th longwall panel),
$\varepsilon_{i}\text{z}$ – maximum horizontal strain caused by exploitation of the $i$-th seam (the $i$-th longwall),
$T_i$ – maximum inclination caused by exploitation of the $i$-th seam (the $i$-th longwall),
$K_i$ – maximum vertical curvatures caused by exploitation of the $i$-th seam (the $i$-th longwall),
$\varepsilon_{z}$ – maximum vertical strain at depth $z$ caused by exploitation of the $i$-th seam,
$\varepsilon_{\text{dop}}$, $T_{\text{dop}}$, $K_{\text{dop}}$, $T_{\text{dop}}$ – values of permissible deformations,
$R_{\text{ign}}$ – value of the most unfavorable length of radius (side) of the pillar (in the case of lengths of longwalls panels optimization $R_{\text{ign}} = 0$),
$R_{\text{imin}}$, $R_{\text{imaks}}$ – lower, upper limit of variation of the pillar radius in the $i$-th seam (in the case of lengths of longwalls panels optimization $R_{\text{imaks}}$ equals to the panel length of the $i$-th longwall).

Limitation (8) allows designing pillars which radiuses increase regularly with the increase of the depth of seams occurrence. In the case of abandoning this limitation, the optimized protective pillar may have a shape that excludes safe off-pillar exploitation (figure 1). Resignation from the use of limitation (8) requires checking if the exploitation of lower occurring seam does not lead to destruction of a higher occurring one.

Figure 1. Diagram of radiuses of protective pillar determined in accordance with Regulation No. 19 – left side of figures (a) and (b) and optimized – right side of figures (a) and (b); (a) – including limitation (8), (b) – without limitation (8).

Due to the fact that when exploitation approaches to the shaft (pit), the maximum of vertical deformations ‘moves’ towards the seam plane and it may happen that for a certain section of the shaft, vertical deformations occurring before the exploitation reaches a predetermined distance, will exceed permissible values even though their final values will be lower than permissible ones. Therefore the calculation of vertical strains is performed with the use of the following scheme (figure 2).

For a given radius of the pillar $R$, the depth of seam occurrence $H$, the radius of the range of influences $r_\alpha$, the value of the pillar’s radius is determined, hereinafter referred to as $R_{kryt}$, for which the off-pillar exploitation evokes maximum vertical strains at a given level $z$. In the case when radius of pillar $R$ is smaller than $R_{kryt}$ determined for the examined level $z$, vertical strains are calculated with the assumption that $R = R_{kryt}$, whereas in the case when radius of pillar $R$ is larger than $R_{kryt}$, calculation of vertical strains is performed with the use of the actual value of radius $R$. The depth $z$, for which $R = R_{kryt}$, is hereinafter referred to as $z_{kryt}$. Thin lines in figure 2 represent the course of $\varepsilon_{z}$ ($R$, $z$) for $R$ varying from 200 m to 40 m. The dashed horizontal line represents the value $z = z_{kryt}$. For
the value \( z \leq z_{\text{kryt}} \), the actual value of \( R \) is taken into account for calculations, while for \( z > z_{\text{kryt}} \), calculations are performed with the use of \( R_{\text{kryt}} \) value. The resulting course \( \varepsilon_z (R, z) \) takes the form of an envelope of curves \( \varepsilon_z (R, z) \) - marked in figure 2 with a thick line.

![Figure 2. Method adopted for determining \( \varepsilon_z (R, z) \).](image)

The developed algorithms assume the possibility of extracting certain seams within the boundaries of the protective pillar (seams for which the maximum deformation indicator values for the half-plane exploitation are lower than permissible ones), which reduces the negative effects of pillar placement, such as relative terrain upheavals and an increase of stresses in rock mass. Also a possibility of imposing pillar radius size in selected seams was considered – which allows leaving the binding pillar boundaries in some seams and adjusting pillar size in the other seams.

In the case of determining a protective pillar for a shaft (pit), it is possible to assume different permissible deformation values for different shaft depths, while during the optimization of a pillar for the group of surface objects it is possible to assume various permissible deformations for individual objects.

The developed algorithms and programs make it possible to determine, separately for each seam, the ‘resourceless zones’, i.e. parts of seams in which exploitation will not be conducted, regardless of the size of protective pillar. Such zones may be for example the areas of geologic disturbances. In particular, a ‘resourceless zone’ may be constituted of abandoned workings of the accomplished mining exploitation, the influences of which have emerged before the erection of an object for which the protective pillar is determined or were taken into account during the assessment of object's resistance.

The problem of determining the protective pillar can also be approached in a different way than the one presented above. Instead of determining boundaries of the protective pillar in successive seams, the scope of the planned exploitation (the lengths of longwall panels) can be optimized to protect the object against influences of mining exploitation. In this approach, the planned longwalls are divided into two groups: fixed longwalls, which panels length is not subject to change and variable longwalls,
which panel lengths are subject to optimization. All plots are divided into rectangles of fixed width. The influences of mining-out the subsequent rectangle are then calculated (i.e. the increase of the values of deformation indicators as well as the extreme values of indicators that have occurred since the beginning of exploitation of the given longwall) for subsequent calculation points. In the case of variable longwalls, the deformation indicator values are calculated for each successive rectangle. While seeking the minimum of an objective function, the limitations (2), (3), (4) and (9) are taken into account, which allows planning the scope of exploitation that does not exclude the subsequent extraction of the remaining deposit.

For seeking the minimum of an objective function (1) the method of a shifting penalty function [3] is used. The above method belongs to the group of approximation methods that solve a sequence of substitutive problems in such modified form, that in subsequent iterations the solutions of these problems are more and more approximated to the solution of the initial problem. Solving of substitutive problems was performed with the use of Powell method, which belongs to the group of non-gradient methods of improvement, i.e. methods determining the solution of a nonlinear programming problem by searching the $R_n$ space in appropriately constructed directions that create the basis of this space. In turn, the minimization in these directions is performed by the non-gradient method of square approximation.

3. An example of determining the protective pillar and optimizing the scope of exploitation

The results of sample calculations of the protective pillar size (the lengths of longwall panels) performed according to the presented methodology are shown below. The simplest situations – determining the optimum protective pillar size for a point object and shaft – were omitted, because of they were already presented in earlier papers [e.g. 4, 5].

3.1. Example 1. Determining the protective pillar for a group of objects with different resistance to the influences of mining exploitation

Figure 3 shows a schematic representation of a surface map showing the objects to be protected. The boundary of protected area was marked too.

![Figure 3](image.png)

**Figure 3.** Boundaries of the protected area, location of protected objects.

Permissible values of horizontal deformations and slopes for protected objects are shown in table 1.
Table 1. Permissible values of deformation indicators.

| Object number | Permissible horizontal strains (mm/m) | Permissible inclinations (mm/m) |
|---------------|---------------------------------------|---------------------------------|
|               | $\varepsilon_x$ | $\varepsilon_y$ | $T_x$ | $T_y$ |
| 1             | 1.5                | 1.5               | 2.5   | 2.5   |
| 2, 3, 5, 6, 7, 8, 9 | 3                   | 3                 | 5     | 5     |
| 4, 10, 11, 12 | 6                   | 6                 | 10    | 10    |
| 13, 14, 15, 16, 21, 22 | 6               | 3                 | 10    | 5     |
| 17, 18, 19, 20 | 3                   | 6                 | 5     | 10    |

It was assumed that under protected objects there occur nine coal seams that would be subject to mining exploitation. Furthermore it was presupposed that the exploitation would be conducted with roof rocks caving and that the resources in each seam are characterised by the same weight. Data on seams is presented in table 2. Table 2 also shows the calculated values of pillars radiuses in individual seams. The values of radiuses determined in accordance with Regulation No. 19 are also included for comparison purposes.

Table 2. Data on seams, results of calculations of pillar radiuses.

| Seam number | Depth of occurrence (m) | Seam thickness (m) | Pillar radius (m) According to Regulation No. 19 | Optimized pillar |
|-------------|-------------------------|--------------------|--------------------------------------------------|-----------------|
| 1           | 370                     | 1.5                | 231                                              | 280             |
| 2           | 470                     | 1.5                | 294                                              | 350             |
| 3           | 540                     | 2.0                | 338                                              | 360             |
| 4           | 680                     | 2.4                | 425                                              | 430             |
| 5           | 750                     | 3.0                | 469                                              | 430             |
| 6           | 800                     | 4.2                | 500                                              | 450             |
| 7           | 900                     | 4.8                | 563                                              | 460             |
| 8           | 930                     | 2.0                | 581                                              | 466             |
| 9           | 960                     | 6.0                | 600                                              | 470             |

The results of optimization are illustrated in figure 4. The “optimized” pillar is characterized by larger radiuses in seams occurring at shallower depths and smaller ones in the case of seams occurring deeper, compared to the values determined in accordance with Regulation No. 19. This trend is in accordance with the results of observations, which indicate that pillars designed with the use of Regulation No. 19, in the case of shallowly occurring seams, were often turning out to be too small.

Figure 4. Diagram of radiuses of the protective pillar determined in accordance with Regulation No. 19 (left side) and the optimized one (right side).
3.2. Example 2. Optimizing the scope of exploitation

In the presented test it was assumed that the protected object (marked with the black circle in figures 5 and 6) would be affected by the influences of mining exploitation designed in two seams marked with numbers 1 and 2. Seam 1 occurs at the depth of 400 m whereas seam 2 occurs at the depth of 500 m. The thickness of seams is 2 m and 3 m respectively. The exploitation takes place in the entire thickness of seams. In seam 1 it was planned to extract the deposit with longwalls 1 ÷ 4 (figure 5a). In seam 2 it is planned to mine longwalls 5 ÷ 8 (figure 5b). It was assumed that deformations occurring in the protected object could not be greater than those permissible for the II category of protection.

![Figure 5. Map of the seam 1 – (a), map of the seam 2 – (b).](image)

The following limitations were imposed on panel lengths of the designed longwalls:

- panel length of longwall 2 should be smaller than panel length of longwall 1,
- panel length of longwall 3 should be smaller than panel lengths of longwalls 2 and 4,
- panel length of longwall 6 should be smaller than panel length of longwall 5,
- panel length of longwall 7 should be smaller than panel length of longwall 6,
- panel length of longwall 8 should be smaller than panel length of longwall 7.

As the result of the conducted optimization, panel lengths of the designed longwalls providing maximization of deposit utilization and at the same time ensuring that the permissible deformations in the area of protected object would not be exceeded were set down. Determined values of panel lengths of the designed longwalls are shown in table 3.

The results of optimization are illustrated in figure 6. The permissible scope of exploitation of the deposit with longwalls 1 ÷ 8 is shown as shaded. Parts of panels of the designed longwalls that should not be extracted to protect the object remained unfilled.
Table 3. Results of calculations of the designed longwalls panel lengths.

| Longwall number | Designed panel length (m) | Optimal panel length (m) |
|-----------------|---------------------------|--------------------------|
| 1               | 700                       | 685                      |
| 2               | 730                       | 626                      |
| 3               | 790                       | 583                      |
| 4               | 820                       | 800                      |
| 5               | 700                       | 681                      |
| 6               | 730                       | 616                      |
| 7               | 790                       | 605                      |
| 8               | 830                       | 598                      |

Figure 6. Optimal panel lengths of the designed longwalls in the seam 1 – (a), in the seam 2 – (b).

The adopted limitations for panel lengths of the designed longwalls allowed obtaining a solution that was acceptable due to the requirements connected with the prevention of rockbursts. It is not ruled out that the remaining parts of the deposit will be extracted later, when the protection of an object is not required anymore.

4. Summary
The decision of establishing a protective pillar, due to many negative consequences of this fact, should be preceded by a careful analysis of the need to set it up. There is no doubt that abandoning the exploitation at sufficiently large distance from the object (i.e. setting up a properly designed protective pillar or determining a suitable scope of exploitation) is a way that enables full protection of the object, even in the case of changes in exploitation plans of a mine caused by, for example, mining disasters or disturbances in seam occurrence. In the case of under-object mining (a variant without
leaving a protective pillar) stopping of the exploitation front, forced by objective causes, may cause damage to the object.

In the case when a pillar is necessary, it is very important to design it properly, so that it can effectively protect the object(s) for which it was established. Protective pillars determined with the use of this method both effectively protect the object and ensure the fulfillment of the criterion of minimizing the amount of resources left in the pillar. In many cases the equally effective solution as setting up of a protective pillar may be optimization of panel lengths of the designed longwall workings.

References

[1] Gruchlik P, Kowalski A, Rajwa S and Walentek A 2014 Modelling of rockmass and surface deformation caused by roadway mining in light of geodetic observations 15. Geokinematisher Tag, 15. und 16. Mai. Freiberg pp 107-16

[2] Jędrzejec E, Kowalski A and Kwiatek J 1996 Determination of protecting pillars for surface buildings, shafts and pits within the boundaries of mining areas of hard coal mines (theoretical foundations and guidelines) (Katowice: Central Mining Institute)

[3] Findeisen W, Szymanowski J and Wierzbicki A 1980 Theory and calculation methods of optimization (Warsaw: Polish Scientific Publishers)

[4] Drzęźla B and Bańka P 1994 Determination of protecting pillar dimensions for surface building and shafts using non-linear method of programming Work Safety and Environmental Protection in Mining 4 pp 39–44

[5] Drzęźla B, Białek J and Bańka P 1995 Protecting pillars – circular or square? Mining Review 5 pp 1–4