Geometrical Description of Gateroad Roof Sag

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ABSTRACT

The main elements of hard coal extraction systems in the Polish mining industry, including the characteristics of gateroads, are described, followed by several dozen underground measurements of gateroad roof sag performed in different geological and mining conditions in Upper Silesia Coal Basin.

Based on the analysis of the roof sag measurements, an attempt to describe the gateroad roof sag process using a geometrical model was made. To build the model, it was assumed that the roof sag curve could be described by three straight lines. The first line describes the roof sag ahead of the longwall face; the second line, the sag at the longwall-gateroad junction zone; and the last line describes the zone behind the longwall face. Determining the intersection points and inclination angles is essential for the model. These model parameters depend on the geological and mining conditions in the gateroad.

Using the statistical computations and analysis, the dependencies between the characteristic points of the gateroad roof sag model and the selected geological and mining parameters were defined. The STATISTICA computer program by StatSoft was used for computation.

This paper presents a simple form of the geometrical description of roadway roof sag progression that is very useful during the gateroad support design process.

INTRODUCTION

The longwall system with caving is the dominant method in European mining in cases of hard coal seam extraction. For instance, in Poland, in 2009, 117 longwalls were driven, with total production of 77.5 million tonnes. In roughly 95% of the longwalls, mining operations were conducted using longwalls with roof caving; the remaining 5% used the hydraulic stowing system. The average mining depth was about 700 m (2,297 ft), and average daily output per face was approximately 2,600 tonnes per day. When using the longwall mining system, gateroads play an important role. These principal roadways transport materials, mine crews, and output. In addition, they impact ventilation of the extraction area, affecting, among other things, the climatic conditions or methane hazard. Unfortunately, difficulties often appear in maintaining an adequate size for the gateroads, due to the face line, which causes origination zones with stress concentration around the gateroad, resulting in rock mass movements in the form of roof sag, floor heave, or horizontal convergence (Figure 1).

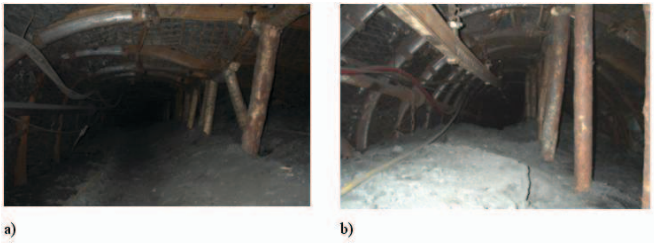

Figure 1. Examples of gateroad deformation (a) deformation of roof-bar arches due to roof sag and (b) heave of floor strata.

Significant gateroad convergence may substantially hinder mining, which would adversely affect work safety and increase production costs. To eliminate convergence, research has been conducted in many countries aimed at detailed recognition of phenomena taking place in gateroads and their surroundings, as well as determining methods of support selection, ensuring stability and adequate opening dimensions. Over the last century, extensive field tests were conducted in Germany, France, and Poland. On the basis of the results, a number of empirical relationships have been isolated, allowing for the prediction of the progression of convergence in the headings located in various geological and mining conditions (Biliński, 1968; Jacobi and Everling, 1967; Jacobi, 1976; Junker, 2006; Kammer, 1977; Schwartz, 1957). More recently, investigations of both the phenomena occurring around the gateroads and gateroad deformation have been conducted using specialized computer programs, allowing for numerical modelling of the phenomena that take place in the rock mass. Programs such as PHASE, UDEC, or FLAC are commonly applied (Barczak et al., 2005; Esterhuizen and Barczak, 2006; Opolony et al., 2004; Prusek and Masny 2007; Prusek, 2008; Ruppel and Scior, 2008; Walentek, Lubosik, Prusek, and Masny, 2009; Zipf, 2006). Examples of numerical modelling application in assessing gateroad deformation are presented in Figure 2.

When selecting the gateroad supports, it is very important to take into account the possible convergence of those workings. Knowing the convergence value of the gateroads located in defined conditions, one can select the supports with specific yield capacity and estimate a value of the cross-section, including the likely convergence.

This paper presents the results of several years of roof strata sag measurements that were conducted in 23 gateroads of longwalls with caving. On the basis of analyses of these test results, and of literature data, a geometrical model of roof strata sag in gateroads has been created. The model is described in detail in this publication.

GEOMETRICAL MODEL OF ROOF STRATA SAG IN GATEROADS

The data used for creating the geometrical were the results of underground vertical convergence measurements conducted in 23 gateroads of retreating longwalls driven with caving (Prusek, 2008). Headgates were maintained on the whole longwall panel length behind the face line. The main data relating to the 23 gateroads are presented in Table 1.

In order to evaluate the sizes of vertical cross-sections of gateroads after the effects of the face line, the underground measurements of vertical and horizontal convergence and floor strata heave have been made. In each of the headings, the measuring bases were set at a distance of 100 m ahead of the face line. The measurements were conducted until the time when the measuring points were found to be about 200 m behind the face line. Within each of the bases, the measuring points were set for measurements of vertical convergence (*z*). The measuring points were sections of steel rock bolts installed in the roof, floor, and sidewalls of the headings. The measurement of convergence relied on determining both the subsequent values of mutual displacement of the points and the distance to the face line nearer or farther from a given measuring station. Figure 3 presents the schematic diagram of the measurement base set in gateroads and a measurement of vertical convergence of the heading behind the face line being recorded.

The results concerning sag of roof strata in the gateroads, calculated as the differences between vertical convergence and floor heave are presented in Figure 4.

When analyzing the measurements in the headings, it has been assumed that the roof sag can be described by means of a simplified model constructed of three straight lines. The first line (P_1) will be running 100 m (328 ft) ahead of the face line; the second (P_2) will approximate the roof sag in the face-heading crossing area; and the third line (P_3) reflects the final phase of roof strata movement behind the face line. It has been assumed that these straight lines will intersect at characteristic points, one before the face line, point *A,* and the other behind the face line, point *B*. This simplified geometric model of roof strata sag in gateroads is presented in Figure 5.

When creating a geometrical model constructed of three straight lines, it was necessary to determine their slopes. An analysis of underground data has revealed that in all 23 cases a small sag before the face line took place; this will be represented by straight line P_1, inclined by $\alpha_1=1°$. The beginning of this line corresponds with the beginning of measurements, a point 100 m (328 ft) ahead of the face, as shown in Figure 5. To draw the second straight line P_2, it was necessary to determine its inclination angle, α_2. Similarly, in the case of P_3, the values of angle α_3 were determined. These model parameters, together with the positions of points *A* and *B* and after a uniform scale has been established, are determined for each investigated gateroad, as show in Table 2.

Based on an extensive analysis of the literature and the author's own experience, the effects of many geological and mining factors on the geometrical model parameters have been considered. After making detailed analyses and statistical computations, the relationships for computation of individual model parameters were obtained.

LOCATION OF "A" POINT OF INTERSECTION OF STRAIGHT LINES P1 AND P2

Point *A,* the intersection of straight lines P_1 and P_2, was the first of the model parameters analyzed. Its position ahead of the face line was found to be dependent on the ratio of maximal vertical stress σ_{zmax} in the seam to compressive strength R_{cw} of the seam and on the average rate of daily longwall advance *v.*

Based on the analysis of values obtained for point A and the value of the expression $\frac{\sigma_{z\max}\cdot\sqrt{v}}{R_{cw}}$ for individual headings, it has been assumed that the interrelation between these values can be described by means of a straight line in the general form $y=ax+b$. Then, using the STATISTICA 8.0 program, the values of coefficients *a* and *b* have been computed by means of linear regression. This is shown in Figure 6.

By substituting the results of statistical computations into the general formula of the straight line, the relationship has been obtained, with correlation coefficient R = 0.83, to calculate the locations of point *A*:

$$A = 1.2456\cdot\left(\frac{\sigma_{z\max}\cdot\sqrt{v}}{R_{cw}}\right)+3.7866\ \text{[m]} \tag{1}$$

where v = average daily longwall advance rate (m/day),

R_{cw} = compressive strength of coal seam (MPa),

σ_{zmax} = maximal stress (pressure) in the seam before the face line, caused by the influence of the face, computed approximately from the following relationship:

$$\sigma_{z\max} = 3\cdot q\ \text{[MPa]} \tag{2}$$

where q = rock mass pressure calculated from the following formula (Biliński, Dreinert, and Kostyk, 1996)

Table 1. Principal geological and mining data of gateroads in which measurements of vertical convergence were carried out.

Working	Depth [m]	Slope of seam [°]	Rc of roof [MPa]	Rc of floor [MPa]	Rc of coal [MPa]	Height of longwall [m]	Length of longwall [m]	Longwall advance [m/day]
Heading 1	750	5.0	37.0	20.0	7.5	2.5	200	6.0
Heading 2	500	5.0	21.6	20.0	14.8	2.0	250	10.0
Heading 3	500	5.0	21.6	20.0	14.8	2.0	250	9.0
Heading 4	500	5.0	26.1	24.2	17.4	2.0	250	11.0
Heading 5	500	5.0	26.1	24.2	17.4	2.0	250	7.5
Heading 6	340	4.0	16.0	16.0	15.0	2.6	250	5.5
Heading 7	600	3.0	22.2	23.2	15.0	2.3	230	6.0
Heading 8	600	3.0	22.2	23.2	15.0	2.3	230	7.0
Heading 9	990	5.0	32.2	39.5	14.7	2.4	345	2.0
Heading 10	970	5.0	32.2	39.5	14.7	2.2	230	3.0
Heading 11	490	6.0	10.0	32.2	32.2	3.0	180	3.5
Heading 12	695	6.0	36.6	15.7	14.9	1.5	321	4.5
Heading 13	550	5.0	18.0	22.4	21.0	1.5	290	4.5
Heading 14	390	8.0	11.4	23.5	22.6	3.0	210	7.0
Heading 15	720	4.0	24.5	32.8	31.3	4.2	186	8.0
Heading 16	710	5.0	31.0	24.0	15.7	2.0	200	5.0
Heading 17	250	5.0	29.5	16.0	16.0	2.8	220	2.0
Heading 18	550	6.0	20.4	16.0	16.0	3.0	205	6.0
Heading 19	525	4.0	23.9	15.0	14.5	2.1	170	5.0
Heading 20	400	6.0	18.0	17.0	5.0	2.5	160	4.5
Heading 21	390	6.0	34.8	20.2	15.8	1.9	250	6.5
Heading 22	311	5.0	14.0	16.1	7.2	2.1	110	3.0
Heading 23	650	6.0	29.0	38.0	17.0	1.8	110	4.0

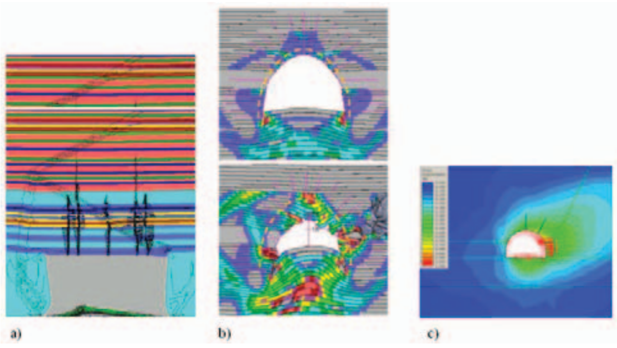

Figure 2. Results of numerical modelling of gateroad deformation (a) deformations of rock mass around gateroad with additional cable rock bolts in the roof (Zipf, 2006); (b) deformation of heading of arch-type cross section supported with rock bolts (Ruppel and Scior, 2008); (c) deformation of heading of arch-type cross section with steel frame supports, together with rock bolts and pack (Prusek, 2008).

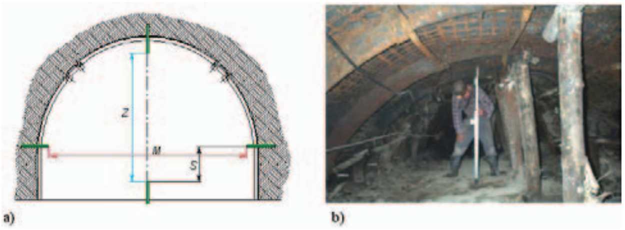

Figure 3. Underground measurements of gateroad deformation (a) scheme of measuring base in gateroads; (b) measurement of vertical convergence behind face line.

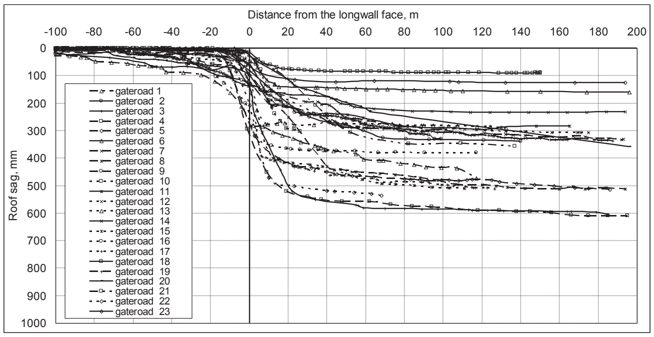

Figure 4. Course of roof strata sag in gateroads vs. face line position.

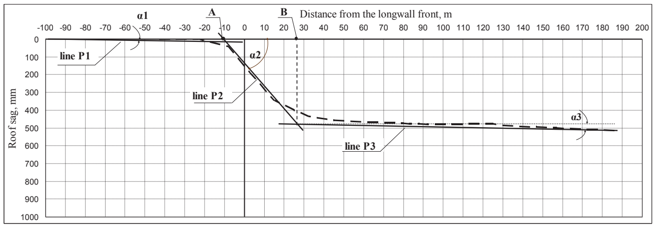

Figure 5. Geometrical model of roof sag in gateroads.

$$q = 0.02 \cdot m_c \cdot G \cdot \cos\alpha \qquad \text{[MPa]} \tag{3}$$

where m_c = *rock mass modification factor (Biliński, Dreinert, and Kostyk, 1996),*

G = depth of mining (m),

α = inclination of seam (degrees).

The value of maximal vertical stress can be exactly calculated through various empirical relationships, or by using analytical methods or numerical modelling. When determining σ_{zmax} to compute point A, it has been assumed that this stress is three times greater than the value of original pressure, an approximation quoted in the literature. Based on various publications, one can say that the maximal stress in the seam extracted with roof caving may range from 0.2 to 6.4 of vertical stress value resulting from the depth (Bieniawski, 1987; Brady and Brown, 2006; Peng, 2006, 2008).

Based on the relationship obtained (Equation 1), one can say that the beginning of roof sag ahead of the face line is conditioned on the ratio of maximal stress in the seam to compressive strength and on the rate of daily advance. When the value of stress exceeds the strength of the seam coal, destruction takes place and a substantial increase in roof strata sag begins. In addition, one can draw a conclusion from relationship (Equation 1) that at increasing longwall advance rates, a substantial rise of roof strata sag in gateroads will begin at a greater distance before the face line.

INCLINATION ANGLE OF STRAIGHT LINE P2 - α2

The value of the inclination angle α_2 of straight line P_2 has been made conditional on the ratio of maximal stress σ_{zmax} in the seam ahead of the face line to the effective mechanical strength of the rock mass, R_{ef} , that directly surrounds the gateroad. When analyzing the values of angles α_2 (Table 2) and the values of ratio σ_{zmax} / R_{ef} computed for each heading, it has been assumed that the relationship between these quantities will be presented as a function of a general form $y = ax^b$. The results of statistical computation, using non-linear regression, have enabled the calculation of the constants *a* and *b* of the function assumed (Figure 7).

After substituting the values of constants *a* and *b* into the general form function, a formula has been obtained, with correlation coefficient R = 0.78, to compute the values of angle α_2:

$$\alpha_2 = 39.4 \cdot \left(\frac{\sigma_{z\max}}{R_{ef}} \right)^{0.4117} \qquad [°] \tag{4}$$

where R_{ef} = the effective mechanical strength of the rock mass, calculated as a weighted average of the compressive strength of rock directly surrounding the gateroad. Depending on the size of gateroad, to calculate the weighted average, one takes into account the strata located in

- The roof, with the range being that of the greater dimension (width or height)
- The sidewalls
- The floor, with the range being a half of greater dimension (width or height)

The value of strength R_{ef} is calculated from the following formula (Łojas and Łaboński, 1980):

$$R_{ef} = \frac{\sum_{i=1}^{n} R_{ef} \cdot m_i}{\sum_{i=1}^{n} m_i}, \text{ MPa} \tag{5}$$

where m_i = thickness of rock stratum (m).

The relationship presented (Equation 4) indicates that the intensity of roof sag in the area of longwall-gateroad crossing depends on the maximal values of stress in the seam, relative to the compressive strength of the rock surrounding the gateroad.

Table 2. Parameters of geometrical model of roof sag in gateroads.

Working	Location of point A (ahead of face) [m]	angle α2 [°]	Location of point B (behind face) [m]	angle α3 [°]
Heading 1	16.0	51.0	30.0	2.7
Heading 2	10.0	51.0	32.0	2.0
Heading 3	10.0	52.0	31.0	2.0
Heading 4	10.0	49.0	27.0	2.0
Heading 5	11.0	50.0	29.0	2.1
Heading 6	6.0	43.0	19.0	2.5
Heading 7	8.0	50.0	28.0	2.3
Heading 8	10.0	46.0	36.0	2.1
Heading 9	17.0	59.0	20.0	2.2
Heading 10	12.5	54.0	23.0	2.0
Heading 11	6.5	45.0	16.0	3.0
Heading 12	12.0	41.0	26.0	1.8
Heading 13	7.0	48.0	18.0	1.9
Heading14	5.0	43.0	14.0	2.5
Heading 15	10.0	53.0	20.0	3.1
Heading 16	15.0	50.0	20.0	2.0
Heading 17	6.0	34.0	25.0	2.2
Heading 18	6.0	48.0	21.0	2.8
Heading 19	11.0	48.0	25.0	2.0
Heading 20	16.0	47.0	18.0	2.5
Heading 21	6.5	32.0	25.0	1.9
Heading 22	11.0	52.0	15.0	2.1
Heading 23	10.0	41.0	23.0	1.9

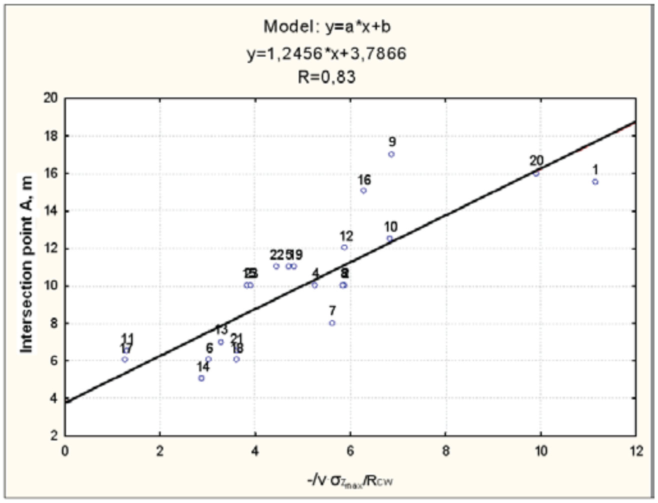

Figure 6. Results of statistical computations and course of the function to calculate locations of point A.

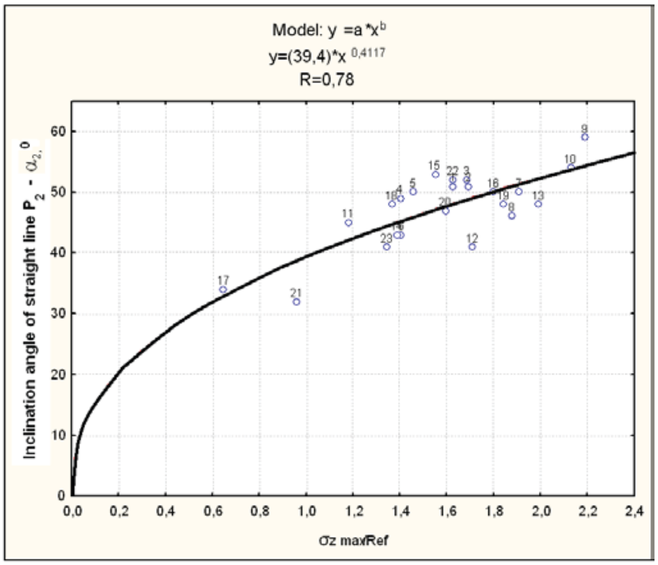

Figure 7. Results of statistical computations and course of function for angle α_2.

LOCATION OF "B" POINT OF INTERSECTION OF STRAIGHT LINES P2 AND P3

The point *B* in the model defines the intersection point of the P_2 and P_3 lines behind the face line. From underground measurements, this point has been located in the headings at a distance from the face line of 14 to 36 m (46 to 118 ft) (Table 2). From this point, a certain stabilization of roof sag takes place. The location of point *B* has been related to lithological structure of roof strata defined as roof number $L_{st,}$ which is calculated from the following relationship (Dubiński and Konopko 2000):

$$L_{st} = \sum (h_i \cdot r_i) \tag{6}$$

where h_i = thicknesses of individual strata of a given rock type up to the height of 100 m above the seam extracted,

r_i = average reduction coefficient; it is equal to 0.31 for coal, 0.29 for mudstone, 0.62 for arenaceous shale, 1.00 for sandstone, 0.04 for caving goaf, and 0.01 for stowing goaf.

The relationship between point *B* and the roof number value, L_{st}, has been determined by means of non-linear regression method after assuming the function of a general form $y = ae^{bx}$. The results for *a* and *b* are presented in Figure 8.

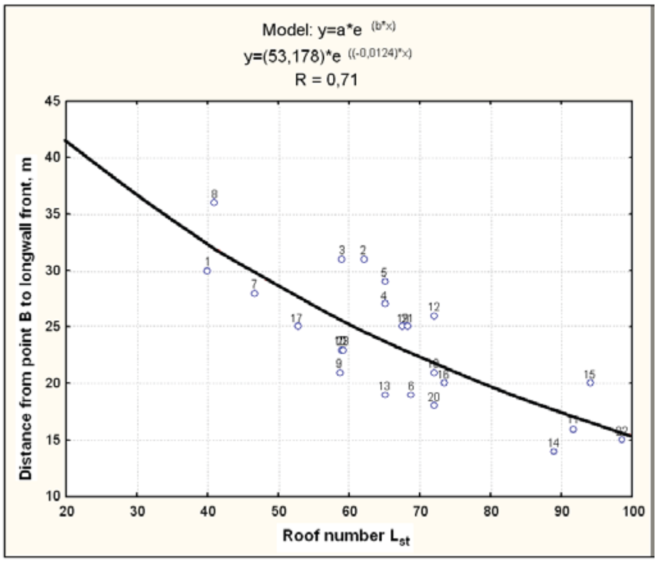

Figure 8. Results of statistical computations and course of function for point B.

With a correlation coefficient of R = 0.71, the formula for the location of intersection B can be presented as follows:

$$B = 53.178 \cdot e^{-0.0124 \cdot L_{st}} \text{ [m]} \tag{7}$$

where L_{st} = roof number.

From the graph presented in Figure 8, it follows that in the case of firm rock with higher L_{st} values, point B occurs closer to the face of the longwall. In this case, lower sag of roof strata occurs, and the distance behind the face at which stabilization of roof strata displacement takes place becomes shorter. When brittle rock with a lower value of L_{st} is deposited in the roof of the seam, roof strata sags at greater distances behind the face.

INCLINATION ANGLE OF STRAIGHT LINE P3 - α3

The inclination angle α_3 of line P_3 is the last parameter of the geometrical model**.** Taking into account, among the other things, the works relating to surface protection against the consequences of mining (Kowalski, 1985; Kwiatek et al., 1997), the inclination of Line P_3 has been made dependent on the height of mining. To determine the relationship with the height of mining, statistical computations using non-linear regression have been made for a function of the form $y=ae^{bx}$. The results are presented in Figure 9.

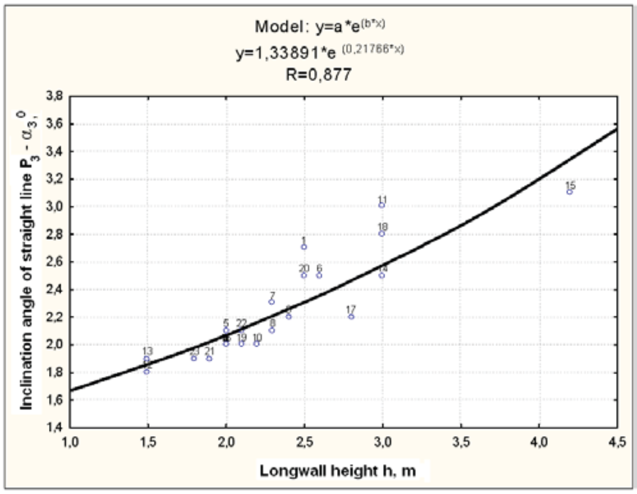

Figure 9. Results of statistical computations and course of function for angle α_3.

The angle α_3 of line $P_{3,}$ with correlation coefficient R = 0.877, is determined from the following formula:

$$\alpha_3 = 1.33891 \cdot e^{0.21766 \cdot h} \, [°] \tag{8}$$

where *h* = height of longwall (m).

From the relationship shown in Figure 9, one can observe that an increase in longwall height results in an increase of the angle α_3, which gives rise to higher values of roof sag in the gateroad.

SUMMARY AND CONCLUSIONS

In Polish hard coal mines over the last years, underground measurements obtained for gateroad deformation in longwalls with caving provided the basis for a geometrical model of roof sag. The model of roof deformation has been based on three intersecting straight lines. By developing the relationships that enable the computation of the intersections *A* and *B* before and behind the face line and the angles of their inclination, the roof deformation can be estimated. The parameters of the model are most affected by maximal value of stress in the seam ahead of face line, compressive strength of roof and floor seam strata, roof number and average daily advance rate, as well as the longwall height.

The relationships allow for the assessment of the progression of roof sag in a given example of planned extraction using longwall mining with caving. Using these computations, mines may obtain preliminary information relative to the intensity of rock mass movements, the possible deformation of supports, or a change of cross sectional area of the gateroads. This information may lead to improved support design or to the application of other methods that limit roof strata sag.

It should be mentioned that the relationships that make it possible to compute the basic model parameters will need to be verified and possibly corrected in the future, or they will need to be extended with additional geological and mining factors.

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