Daily coal mining as a factor influencing methane concentration at a longwall – a case study

Henryk Badura¹ and Zygmunt Łukaszczyk²

¹ Faculty of Mining and Geology, Silesian University of Technology, Akademicka 2, 44-100 Gliwice, Poland
² Faculty of Organization and Management, Silesian University of Technology, Roosevelta 26-28, 41-800 Zabrze, Poland

zygmunt.lukaszczyk@polsl.pl

Abstract. This paper describes an exemplary method of presenting the average concentration of methane at the outlet of one of walls in the “Krupiński” mine. This method involves the linear function of current mining and mining on preceding days. The ordinary least squares method used to determine parameters of that function was found to produce too serious errors. Therefore, it is recommended to use one of generalised least squares method. In this case Cochrane-Orcutt estimation for the generalised least squares method was applied. Measured and approximated values of methane concentration showed good compliance. Also, parameters of the approximation function for the average concentration of methane was determined. It was a linear function of the square root of mining on the current day and the preceding days. For that purpose, Cochrane-Orcutt procedure was also applied. Results from approximation by mentioned functions were nearly identical.

1. Introduction

Many gas, geological, mining, technical and organizational factors and parameters affect methane hazards at the longwall. Daily mining belongs to them. Karacan C.Ö [1] cited a view of L.W. Łunarzewski [2] that emission of methane at the longwall could be described using the following equation:

\[ V = a \sqrt{CP} + b \]

Where: \( V \) – total emission of methane (l/s), \( CP \) – daily mining (t/day), \( a, b \) – equation parameters approximated on the basis of observations.

Total emission of methane is regarded as the sum of methane emitted from the exploited seam, roof and floor rocks. The same opinion had been already presented by [3].

Many papers on predicting methane emission to pits at the longwall [4, 5] assumed there was a linear relationship between the total emission of methane and daily output. According to [6], emission of methane was proportional to daily mining, however they corrected the predicted amount of emitted methane taking into account the progress at the longwall.

Barker-Read and Radchenko [7] described the potential application of time series for modelling variations in methane concentration in mines. They tested correlations between the volume flow of methane subjected to degasification and variations in methane concentration in pits.
Statistical approach towards predictions of methane emission on a weekly rate were applied in Lorraine, France [8].

The paper [9] proposed the application of neural networks to predict methane content in pits and the volume flow of methane subjected to degasification.

The paper [10] presented an opinion that there was some correlation between the average value of methane emission on a specific day and daily output on a specific day and preceding day. Methane emission was defined using the following equation:

$$V = a + bW + cW_{-1}$$

(2)

Where: $V$ – volume flow rate of emitted methane (m$^3$/min), $W$ – coal mining on the current day (Mg/day), $W_{-1}$ – coal mining on the preceding day (Mg/day), $a$, $b$ – parameters of equation.

Methane concentration, and not its volume emitted per time unit, directly poses methane hazard in mine pits. Imposing restrictions on methane emission at the longwall per time unit is connected with technical possibilities of methane dilution to safe levels.

Volume flow of methane emitted to pits at the longwall is calculated on the basis of measured concentration of methane and the rate of air flow through pits of the defined cross-section. Thus, the predicted concentration of methane is required to calculate the expected volume of methane emitted into the ventilation air.

Methods of approximating time series of the average methane concentration (with reference to 24 hours) at the outlet of “U” ventilated longwall, by the linear function of current mining and mining on preceding days are described further in this paper.

2. Natural and mining conditions of the longwall N-6 in the coal seam 330/2

Bedding conditions for a part of the coal seam 330/2, where the longwall N-6 was exploited, were explored through five drill holes, two of them at the surface (BS-30/1981, BS-3/1972), and three holes in the underground pits (G-23/2005, G-24/2005 and G-17/2007) and through preparatory pits at the longwall N-6. Fragments of geological profiles from holes BS-3/1972 and G-23/2000 are illustrated in figure 1, and geological section of the seam parallel to face of the longwall N-6 are shown in figure 2.

The analysis of geological profiles shows that geological conditions for seam bedding were very changeable. For example, in the hole BS-3/1972, directly over the seam, there were cracked dark grey claystone with a thickness of 1.80 m, cracked light grey sandstone with a thickness of 1.60, sandy grey claystone with a thickness of 9.8 m. Over those strata, there was the first stratum of coal and coal with clay, having a total thickness of 0.8 m. And the total thickness of rock strata indicated that coal stratum was over the seam 330/2 within a distance of 13.20 m.

In the hole G-23/2000, there were the following strata over the seam 330/2: claystone with a thickness of 0.30 m, sandy claystone with sandstone interbed with a thickness of 6.10 m, sandstone with a thickness of 2.20 m, and sandy claystone with a thickness of 5.70 m. A stratum of coal with a thickness of 1.0 m was deposited over the above strata, that is, within a distance of 13.0 m.

It implies that rock strata between the seam 330/2 and the unnamed coal stratum differed in mineralogical and petrographic composition and thickness. Also, coal stratum differed in thickness and contamination with mine waste.

Profiles illustrated in figures 1 and 2 demonstrate that the seam 330/2 is divided into strata by parting of mine waste. The quantity and thickness of strata differ depending on coordinates of the analysed geological profile. In the hole BS-3/1972 (figure 1), thickness of the seam was 3.50 m, of which coal strata constituted 54%. In the hole G-23/2000 (figure 1), coal stratum had a thickness of 1.10 m and formed a single layer with a high content of claystone at the roof part.

In the profile of the longwall face, at which exploitation was performed (figure 2), near the heading N-6, thickness of the seam was 2.66 m, of which 64% was constituted by coal strata (1.69 m). In the point at a distance of ca. 90 m from the heading N-6, the seam thickness was 2.48, and thickness of
coal strata was 1.48 m (60% of the seam thickness). In the point at a distance of ca. 210 m from the heading N-6, the seam thickness was 2.85, and thickness of coal layers was 1.77 m (62%).

**Figure 1.** Fragments of geological profiles from the hole BS-31/1972 (on the left) and the hole G-23/2000 (on the right).

**Figure 2.** Geological section through the seam 330/2 parallel to the longwall face.
Strength of roof rocks determined by tests on core specimens, was within the range from 53.5 MPa to 75.1 MPa, and strength of floor rocks was within the range from 22.0 MPa to 41.2 MPa. Strength of the coal seam 330/2 was between 14.0 MPa and 16.0 MPa.

Geological profiles indicated some non-exploitable seams within a short distance from the seam 330/2. Mineral strata with a considerable content of coal were also found in the bed. Such layers are also the source of sorbed methane.

Distance from other exploitable seams over the seam 330/2 varied. And the nearest seam 329/1, 329/1-2, which had been previously exploited, was within a distance from 35 m to 75 m.

The predicted total methane concentration at the longwall N-6 was 30.14 m³/min for the planned output at the level of 4000.00 Mg/day. According to the forecast, ca. 48.6% of total methane content would origin from overlaying rocks, 26.5% from the exploited seam, and 24.9% from strata below the seam 330/2.

The longwall G-6 (figure 3) had the following geometric parameters:
- length - ca. 225 m,
- panel length - ca.1100 m,
- height from 2.80 to 2.96 m.

![Figure 3. Scheme of pits at the longwall N-6 in the seam 330/2.](image)

The exploited initial part of the longwall N-6 was under the seam where no exploitation works were performed. However, at the further panel of the longwall, the exploitation area was partially mined. Therefore, exploitation resulted in longer section of the wall under the depleted part of the seam 329/1, 329/1-2.

The following workings were prepared to conduct mining area at the longwall N-6. The heading N-6 was made from the incline N-4 in the seam 330/2. A top gate N-6 was made from the heading N-4, which served as a bottom gate for the longwall N-4. The top gate was separated from the heading N-4 with a narrow coal pillar. The heading N-6 and the fail gate N-6 were connected by means of the raise N-6.

Fresh air from the incline N-4 in the seam 330/2 was passing through the heading N-6 to the longwall N-6. Air used for ventilating the longwall was exhausted through the top gate N-6 to the heading N-4. Exhaust air was flowing through the heading N-4 to the intersection with the air hole N-4. There, it mixed with fresh air flowing from the incline N-4 in the seam 330/2, stopped by a segment of the heading N-4. Starting from the intersection, exhaust air was discharged through the air hole N-4 to more distant pits, towards the ventilating shaft.
At the initial stage, mining in the panel of 220 m, at the longwall N-6 was performed under a non-exploited part of the bed. The longwall in the mining area was further located under the mined out part of the seam 329/1, 329/1-2 shown in figure 3 as a shaded beige area. Because the distance between seams 330/2 and 329/1, 329/1-2 was within the range from 35 m to 70 m, mining in the seam 329/2, 329/1-2 caused a partial methane drainage from the seam 330/2 and rock strata between those seams, mainly in the part bedded directly under old pits in the seam 329/1, 329/1-2.

The average monthly progress at the longwall was 105 m, that is ca. 5 m per a working day.

3. Measured data

The forecast of methane concentration was mainly based on telemetric measurements. A methane sensor was placed on the route of exhaust air flow in the heading N-4, before the intersection with the air hole N-6 (figure 3). A measurement error of the methane sensor was 0.1% CH$_4$. The forecast was prepared and verified using measurements from the period from 23.05.2013 to 04.02.2014, that is 258 days, including 175 working days. Non-working days means Saturdays, Sundays and public holidays. The first day of observations was also the last day of mining at the longwall N-6.

Measured data were processed with the software PROGMET developed in the Institute of Mining at the Silesian University of Technology [11]. Calculated results included, inter alia, average values of methane concentration and its minimum and maximum values. Average values of methane concentration were calculated for 24-hour periods, starting at 6:00:00 a.m. on the day of measurements and ending at 5:59:59 a.m. on the following day, which was consistent with the mining cycle.

Values of average concentration of methane formed a time series. Autocorrelation was observed between terms in the time series. Autocorrelation coefficient of terms in the series was very high, equal to $r_a = 0.92$.

Average volume flow of the air was the second measured parameter. It involved the same periods on the basis of continuous measurements of the air flow rate. A stationary anemometer was located near the methane sensor. Figure 4 illustrates values of average measured concentration and average volume flow of the air within the analysed period.

![Figure 4. Average concentration of methane at the outlet of the longwall and volume flow of the air passing through a ventilating road.](image-url)

The presented graphs show that the relationship between methane concentration and volume flow of the air was poor. The above was confirmed by correlation coefficient between those parameters,
equal to \( r = 0.27 \). Therefore, it can be stated that changes in volume flow of the air did not significantly affect variations in methane concentration. This could be explained by the fact that increased air flow through the longwall area was connected with reduced methane concentration. And the accompanying drop in atmospheric pressure fostered the outflow of methane, and consequently led to an increase in methane concentration. Figure 5 presents graphs of methane concentration and daily output.

**Figure 5.** Average concentration of methane at the outlet of the longwall and daily output at the longwall.

The analysis of graphs points to conclusions that the value of the correlation coefficient between discussed values is \( r = 0.43 \), and the relationship between methane concentration and daily output is poor, but still important.

And the relationship between average concentration of methane and mining on the preceding day was slightly more significant, because the correlation coefficient between those values was \( r = 0.48 \).

The calculated coefficient of correlation between the average concentration of methane and output from two days earlier was \( r = 0.32 \). Thus, this coefficient was important, but also low.

**4. Approximation of average concentration of methane at the outlet of the longwall**

Parameters of the following relationship were determined to describe analytically the impact of mining on the average concentration of methane, taking into account significance of correlation between methane concentration and mining:

\[
S_a = a_0 + a_1 W + a_2 W_{-1} + a_3 W_{-2} \tag{3}
\]

where: \( S_a \) approximate value of average concentration of methane, \( W, W_{-1}, W_{-2} \) mining on the current day, preceding day, and from two days earlier, respectively, \( a_0, a_1, a_2, a_3 \) – parameters.

The following equation describes the real value of average concentration of methane:

\[
S_{r, i} = a_0 + a_1 W_{i} + a_2 W_{-1,i} + a_3 W_{-2,i} + \varepsilon_i = S_{ai} + \varepsilon_i \tag{4}
\]

where: \( S_{r, i} \) – i-th measured value of average concentration of methane, \( S_{ai} \) approximated i-th value of average concentration of methane, \( W_{i}, W_{-1,i}, W_{-2,i} \) – i-th values of mining on the current day, preceding day, and two days earlier, \( \varepsilon_i \) – i-th difference between approximated and measured value of average concentration of methane (i-th residuals).
The ordinary method of least squares was used to determine parameters \( a_0, a_1, a_2, a_3 \). GRETL software was applied for that purpose [12]. Calculated results are shown in the table below.

The corrected coefficient of determination was \( R^2 = 0.39 \), thus the coefficient of correlation was \( r=0.62 \). The calculated value of autocorrelation coefficient for differences (a random component, residuals) between the measured and calculated value of average concentration of methane was very high, equal to 0.82. It means that results from approximation calculated with the ordinary method of least squares could demonstrate a bias of results. It is confirmed by the graph illustrating the relationship between measured and calculated results of methane concentration (figure 6).

| Parameter | Parameter value | Standard error of the parameter | Probability of statistical insignificance of the parameter |
|-----------|-----------------|--------------------------------|---------------------------------------------------------|
| \( a_0 \) | 0.34977         | 0.0285694                      | <0.0001                                                 |
| \( a_1 \) | 0.00005831      | 7.74622e-06                    | <0.0001                                                 |
| \( a_2 \) | 0.00003802      | 7.96805e-06                    | <0.0001                                                 |
| \( a_3 \) | 0.00004544      | 7.73799e-06                    | <0.0001                                                 |

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Figure 6. Relationship between average concentration of methane which was measured and approximated with the equation (3), where values of coefficients were estimated with the ordinary method of least squares.

In case of an ideal correlation between approximated and measured average concentration of methane, the value of determination coefficient should be equal to \( R^2 = 1 \) (and true value is \( R^2 = 0.3965 \) – not corrected), the value of coefficient for the variable \( x \) from the presented equation should be 1 (true value is 0.3965), and the value of the second term of the equation should be 0 (true value is 0.4068).
| Parameter | Parameter value | Standard error of the parameter | Probability of statistical insignificance of the parameter |
|-----------|----------------|-------------------------------|---------------------------------------------------|
| $a_0$     | 0.5028190      | 0.0782432                    | <0.00001                                          |
| $a_1$     | 0.0000287      | 2.51534e-06                  | <0.0001                                          |
| $a_2$     | 0.0000281      | 2.37232e-06                  | <0.0001                                          |
| $a_3$     | 0.0000124      | 2.51457e-06                  | <0.0001                                          |

Regarding autocorrelation of terms in time series of the average concentration of methane, parameters for approximation should be determined using one of generalised least square methods [14]. For the purpose of this paper, the Cochrane-Orcutt procedure, being a sub-programme in the GRETL software, was used to determine parameters of the equation (3). Values of parameters are presented in table 2.

It is noticeable that determined values of parameters (table 2) differed significantly from parameters determined with the ordinary method of least squares (table 1). All parameters of the function (3) were significant because the probability of setting them to zero was lower than 0.0001, that is, considerably lower than 0.05 assumed as the limit value.

The corrected coefficient of determination was $R^2 = 0.92$, which was very high. Autocorrelation of residuals was $r_a = 0.94$.

Individual approximate values of time series for the average concentration of methane should be calculated according to the following procedure:

- calculate average concentration of methane $S_i$ on the basis of parameters from table 2. Regarding delay in obtaining mining values, calculations started on the third day of observations

$$S_i = a_0 + a_1 W_i + a_2 W_{-i_1} + a_3 W_{-2i} \quad \text{for } i = 3, 4, ..., 258 \quad (5)$$

- calculate differences $R_i$ between measured values of average concentration of methane $S_{pi}$ and values calculated according to the equation (5)

$$R_i = S_{pi} - S_i \quad (6)$$

- calculate corrections $P_i$

$$P_i = r_a R_{i+1} \quad \text{for } i = 4, 5, ..., 258 \quad (7)$$

where $r_a$ was autocorrelation coefficient of residuals (differences $R_i$),

- calculate the approximated average value of methane concentration $S_{ai}$

$$S_{ai} = S_i + P_i \quad \text{for } i = 4, 5, ..., 258 \quad (8)$$

where $S_{ai}$ is i-th term in time series approximated to values of methane concentration, $r_a$ autocorrelation coefficient of residuals.

Figure 7 illustrates the graph for correlation between measured values of average concentration of methane and its values approximated with the generalised least square method using the Cochrane-Orcutt estimation.

Mapping the distribution of average measured concentration using the Cochrane-Orcutt procedure is much more precise than in case of the ordinary method of least squares. This is due to the fact that the gradient of the straight line was closer to 1, and an intercept was closer to 0 (figure 7) compared to parameters determined with the ordinary method of least squares (figure 6).
Figure 7. Relationship between average concentration of methane measured and approximated with the equation (3), where values of coefficients were estimated with the generalised method of least squares using the Cochrane-Orcutt estimation.

Comparison of estimation results for the function parameters (3) determined by the ordinary method of least squares and the Cochrane-Orcutt method confirmed that approximation results obtained from the equation (3), for which parameters were determined by the Cochrane-Orcutt method, were substantially more precise than in case of the ordinary method of least squares.

Figure 8 presents graphs of time series of measured and approximated values of average concentration of methane.

Figure 8. Average concentration of methane, measured and approximated with the equation (3), whose parameters were determined with the method of Cochrane-Orcutt.

Figure 9 illustrates the distribution of absolute errors for the discussed approximation.
There were 152 absolute errors in the range [0%, 0.05%] of methane concentration, which constituted 60% of all errors. In the error range [0.05%, 0.10%] of methane concentration, there were 79 errors, which constituted 31% of all absolute errors. Thus, ca. 91% of all absolute errors for approximation were within the range of methane concentration from 0% CH$_4$ to 0.1%CH$_4$.

Percentage contribution of errors within the assumed ranges is illustrated in figure 10. The graph shows that all absolute errors (100%) were within the range from 0.00% to 0.40% CH$_4$, and 96% of absolute errors were not greater than 0.15% CH$_4$.

The number of relative errors lower than 10% of true value was 176 (figure 11). And within the range [10% ÷ 20%], there were only 66 relative errors. Only 13 relative errors exceeded 20% of the true value.
Figure 11. Distribution of relative errors for average methane concentration approximated with the equation (3).

The graph illustrated in figure 12 shows that relative errors, whose values did not exceed 10%, constituted 69% of all errors, and ca. 95% of all relative errors were within the range [0% – 20%].

Figure 12. Percentage contribution of relative errors for average concentration of methane approximated with the equation (3).

Taking into account opinions that methane content (volume flow of emitted methane) at the longwall could be regarded as the root function of daily mining, and simultaneously considering the above results, tests were performed to determine the extent to which time series of methane concentration could be approximated with the following equation:

\[ S_u = a_0 + a_1 \sqrt{W} + a_2 \sqrt{W_{-1}} + a_3 \sqrt{W_{-2}} \]  

Equations (9) and (3) have the same terms.

The same time series of average methane concentration, like in the above examples, was used to determine parameters of the above equation. Parameters of the equation (9) were also determined by the method of Cochrane-Orcutt. Table 3 presents estimated values of parameters of the equation (9).
Table 3. Parameters of the equation (9) determined by the generalised method of least squares using the Cochrane-Orcutt estimation.

| Parameter | Parameter value | Standard error of the parameter | Probability of statistical insignificance of the parameter |
|-----------|-----------------|---------------------------------|-------------------------------------------------------|
| $a_0$     | 0.5038010       | 0.0872003                       | <0.0001                                               |
| $a_1$     | 0.0016538       | 0.0001580                       | <0.0001                                               |
| $a_2$     | 0.0016687       | 0.0001467                       | <0.0001                                               |
| $a_3$     | 0.0006712       | 0.0001580                       | <0.0001                                               |

According to data from the table, all parameters of the equation (9) were significant. The approximated corrected coefficient of determination was $R^2 = 0.91$, which was very high. Coefficient of correlation $r = 0.95$. Figure 13 presents the correlation between average measured and approximated concentration of methane.

![Figure 13](image_url)

**Figure 13.** Relationship between average concentration of methane measured and approximated with the equation (9), whose values of coefficients were estimated with the generalised method of least squares using the Cochrane-Orcutt estimation.

The equation of the straight line shown in figure 13 is nearly the same as in figure 7. Gradients and intercepts of straight line equations were equal to three decimal places.

Also, figure 14 shows that measured values of average concentration of methane were precisely represented by approximated values.

Figures 15 and 16 illustrate the distribution of absolute errors for average concentration of methane approximated with the equation (9).

Within the range $[0\% \div 0.05\%]$ of methane values, there were 142 absolute errors which constituted 56% of all errors. And 89 errors were found within the range $[0.05\% \div 0.10\%]$ of methane, that is, ca. 35% of all absolute errors. Fourteen absolute errors (5% of all absolute errors) were within the range $[0.10\% \div 0.15\%]$ of methane values.

Thus, 56% of all errors were within the range $[0\% \div 0.05\%]$ of methane values, 91% of all absolute errors were within the range $[0\% \div 10\%]$, and 96% of all relative errors were within the range $[0\% \div 0.15\%]$. 
Figure 14. Average concentration of methane, measured and approximated with the equation (9), whose parameters were determined with the method of Cochrane-Orcutt.

Figure 15. Distribution of absolute errors for average concentration of methane approximated with the equation (9).

Figure 16. Percentage contribution of absolute errors for average concentration of methane approximated with the equation (9).
Figures 17 and 18 show distribution of relative errors. Figure 17 indicates that an absolute error did not exceed 10% of true value in 170 cases, and was within the range of 10%, 20% in 70 cases. Nine relative errors belonged to the range of 20%, 30%.

There were 67% of relative errors in the range [0% \( \div \) 10%], and as much as 94% of relative errors in the range [0% \( \div \) 20%]. The range [0% \( \div \) 30%] included 98% of all relative errors (figure 18).

![Figure 17](image1.png)

**Figure 17.** Distribution of relative errors for average concentration of methane approximated with the equation (9).

![Figure 18](image2.png)

**Figure 18.** Percentage contribution of relative errors for average concentration of methane approximated with the equation (9).

The sum of absolute errors of approximation with the function described by the equation (3) was 13.40, and with the function described by the equation (9) - 14.04. Sums of relative errors were 2367 and 2254, respectively.

The analysis of approximation of errors led to conclusions that in the discussed case differences in accuracy of both methods were in favour of the first method, that is, the method in which daily mining and mining from two preceding days was considered as the independent variable. However, the differences were so minor that both methods can be regarded equivalent in this case.
Figure 19. A graph showing accuracy of representing average concentration of methane with the functions (3) and (9).

It is confirmed by the graph in figure 19 showing a relationship between values of average concentration of methane calculated according to equations (3) and (9). The coefficient of gradient was different from 1 by 0.0007, the intercept was different from 0 by 0.0005, and the coefficient of determination was different from 1 by 0.0017.

5. Conclusions
The analysis described in this paper can lead to the following conclusions:
1. Average concentration of methane at the longwall on a specific day affects mining on that day and may affect mining on the preceding days. Estimation of parameters of the function describing the relationships between methane concentration and mining within the specific period can determine which day of mining had a significant impact on average concentration of methane. Significance of mining on a specific day is determined by probability for zeroing of the function parameter with reference to that day.
2. For calculations, the maximum index of parameter insignificance was 0.05, thus the probability of parameter zeroing was lower than 5%.
3. The analysis of literature shows that experts on methane hazards cannot reach consensus where methane content in the longwall depends on mining or the square root of mining. These papers compare results obtained from both methods.
4. The performed calculations show that methane concentration for the analysed period of mining was affected by mining on the specific day and two preceding days.
5. The coefficient of determination calculated for approximation by the function (3) was $R^2=0.92$, and approximation by the function (9) was $R^2=0.91$. It means that variations in average concentration of methane were caused in ca. 92% by mining on the current day and two preceding days, or in ca. 91% by square root values of mining on the current day and two preceding days.
6. Values of absolute errors not exceeding 0.1% of CH$_4$ constituted 91% of all absolute errors of approximation in both calculating cases.
7. Relative errors, whose values slightly exceeded 20%, constituted ca. 95% of all relative errors in case of approximation with the function (3), and ca. 94% of all relative errors in case of approximation with the function (9).
8. The comparison of approximation results (figure 19) hardly indicates any difference in results obtained by approximation with functions (3) and (9).
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