



Analysis of Drill Spasing Based on Coal Thickness and Quality Variability for Coal Resouces in Musibanyuasin

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Abstract: Drill spacing determination is one of the important aspects of coal exploration planning because it directly affects geological confidence, resource estimation, and exploration cost efficiency. This study was conducted on Seam F of the Muara Enim Formation in Musi Banyuasin Regency, South Sumatra. The objective of this study is to evaluate the quantitative variability of coal thickness and quality and to determine the optimum drill spacing as a basis for future exploration planning. The analyzed parameters include coal thickness, ash content, total sulfur, and calorific value. The dataset consists of 115 collar points for coal thickness and 71 collar points for coal quality, with an average existing drill spacing of approximately 422 m. The methods used in this study include descriptive statistics, omnidirectional variogram analysis, global estimation variance (GEV), and relative error (RE). Drill spacing simulation was carried out using spacing scenarios ranging from 100 m to 3000 m to evaluate changes in estimation uncertainty with increasing drill hole distance. The results show that Seam F has an average thickness of approximately 3.19 m with a coefficient of variation (CoV) of 0.06, indicating low thickness variability. Coal quality parameters also show relatively low variability, with CoV values of 0.04 for ash, 0.05 for total sulfur, and 0.01 for calorific value. However, geostatistical analysis indicates that each parameter has different spatial continuity characteristics. Total sulfur has a nugget ratio of 11.7%, indicating relatively good spatial continuity, whereas calorific value has a nugget ratio of 60.8%, indicating stronger local variability. The GEV and RE analyses show that estimation uncertainty increases as drill spacing becomes wider. Based on RE thresholds for coal resource classification, the recommended optimum drill spacing for Seam F is 550 m for measured resources, 825 m for indicated resources, and 1,650 m for inferred resources. This study shows that the integration of descriptive statistics, variogram analysis, GEV, and RE can provide a quantitative and objective basis for determining drill spacing in future coal exploration planning.

Keywords: Coal Thickness; Coal Quality; Drill Spacing; Global Estimation Variance; Relative Error.

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Introduction

Coal exploration planning requires reliable information on coal seam variability to determine an appropriate drilling strategy and to optimize exploration costs. In coal deposits, drill spacing is one of the main factors controlling the level of geological

confidence in resource estimation. If drill spacing is too wide, the uncertainty of thickness and coal quality data may increase. Conversely, overly close drill spacing may increase exploration costs without a proportional reduction in data uncertainty. Therefore, drill spacing evaluation can provide quantitative justification based

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on the spatial variability of data to determine an optimum drill spacing that supports more efficient and accurate exploration planning.

The study area is in Musi Banyuasin Regency, South Sumatra, within the Muara Enim Formation, which is known as a coal-bearing formation (Gafoer, 1992). This formation contains several coal seams with different thickness and quality characteristics, influenced by sedimentary fluctuations in a deltaic environment (Barber et al., 2005). In this study, the analysis focuses on Seam F because this seam is a basal seam with higher economic value compared to other seams. The analyzed parameters include coal thickness, ash content, total sulfur, and calorific value. These parameters are important because they directly influence coal resource estimation and the planning of future exploration drilling programs.

A quantitative approach is required to evaluate the variability and spatial continuity of Seam F. Descriptive statistics are used to measure the distribution and relative variability of coal thickness and quality parameters, while geostatistical analysis is used to evaluate their spatial continuity (Marwanza, 2023; Heriawan et al., 2022). Variogram parameters, including nugget, sill, range, and nugget ratio, provide information on the degree of local variation and spatial continuity of data between drill holes. This information is useful for point-to-point and block-to-point simulations using grid sizes from 100×100 m to 3000×3000 m, which are then used to identify global estimation variance (GEV) and relative error (RE) for determining and justifying the addition or reduction of drill hole spacing (Heriawan et al., 2022).

Previous studies on coal drill spacing analysis have generally relied on qualitative geological assessment, such as the geological condition classification described in SNI 5015:2019. Although this approach is useful for describing whether a coal deposit is simple, moderate, or complex based on sedimentary continuity, structural complexity, and coal quality variation, it may not be sufficient to quantify estimation uncertainty or to justify the economic implications of drilling density. "In addition, the Australian Guidelines for the Estimation and Classification of Coal Resources 2014 and the JORC Code 2012 emphasize that resource classification should consider geological confidence, data spacing, data quality, and, where appropriate, geostatistical assessment to support the level of confidence in resource estimation." Consequently, the relationship between geological variability, drill spacing, estimation confidence, and exploration cost efficiency is often not clearly explained.

Global estimation variance (GEV) and relative error (RE) are applied to evaluate estimation uncertainty under various drill spacing scenarios. These scenarios

represent possible drilling configurations and are used to assess how estimation uncertainty changes as drill spacing increases. A lower RE value indicates lower estimation uncertainty and a higher level of confidence, whereas a higher RE value indicates greater uncertainty.

The objective of this study is to evaluate the quantitative variability of Seam F thickness and coal quality and to determine the optimum drill spacing that can be used as a basis for future exploration planning. The results of this study are expected to support a more effective drilling strategy, improve the reliability of coal resource classification, and help optimize exploration costs in the Musi Banyuasin area.

Method

This study uses a quantitative approach to evaluate the variability of coal thickness and quality in Seam F and to determine the optimum drill spacing based on estimation uncertainty. The data used in this study consist of Seam F thickness data obtained from drilling and wireline log interpretation, as well as coal quality data including ash content, total sulfur, and calorific value from ASTM-standard laboratory analysis using ply-by-ply sampling. The Seam F thickness dataset consists of 115 collar points, while the coal quality dataset consists of 71 collar points with available laboratory analysis data **Figure 1**. Spatially, the drill holes are distributed across the study area with an average drill spacing of approximately 422 m, representing the existing data configuration used for the drill spacing evaluation. The datasets were analyzed using descriptive statistics to determine data characteristics and variability levels, geostatistical analysis using variograms, global estimation variance (GEV), and relative error (RE).

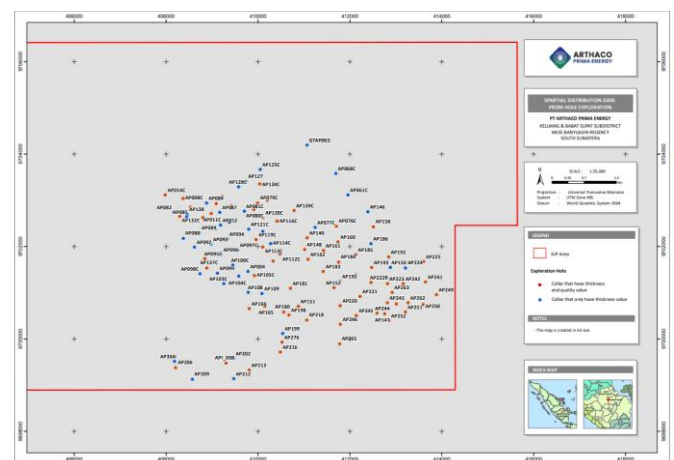


Figure 1. Spatial distribution of the data used for the analysis

The first stage of the analysis was descriptive statistics. This stage was conducted to understand the

characteristics and variability of Seam F thickness and quality parameters. The statistical parameters used include mean, median, mode, minimum, maximum, range, standard deviation, variance, coefficient of variation (CoV), skewness, and kurtosis. The CoV was used to assess the relative variability of each parameter (Marwanza, 2023). A lower CoV value of less than 0.50 indicates more homogeneous data, while a higher CoV value of more than 1.50 indicates greater variability (Heriawan et al., 2022).

The second stage was geostatistical analysis using omnidirectional variogram modeling. Variogram analysis was used to evaluate the spatial continuity of Seam F thickness and quality parameters. Experimental variograms were calculated using lag distances of up to 2000 m and fitted using the least squares method.

$$\gamma(h) = \frac{1}{2N} \sum_{i=1}^n (X_i - X_{i+h})^2$$

where $\gamma(h)$ is the variogram value at lag h , which represents the degree of dissimilarity between data values separated by a certain lag distance. X_i is the data value at location i , X_{i+h} is the data value at a location separated by distance h from i , and n is the number of observations (Isaaks et al., 1989; Pyrcz et al., 2014).

The main variogram parameters analyzed in this study include nugget, sill, range, and nugget ratio (Figure 2) (Isaaks et al., 1989; Pyrcz et al., 2014; Marwanza, 2023). The variogram model used in this study is the spherical model. This model initially shows a linear increase, then gradually flattens until it reaches the sill. In the spherical model, the range is the distance at which the variogram fully reaches the sill.

$$\gamma(h) = 1.5 \frac{h}{a} - 0.5 \left(\frac{h}{a}\right)^3$$

where $\gamma(h)$ is the variogram value at lag distance h . The variogram describes how large the difference is between values of a variable, such as coal thickness or coal quality, at two points separated by distance h . The value of h represents the lag distance or spatial distance between two observation points.

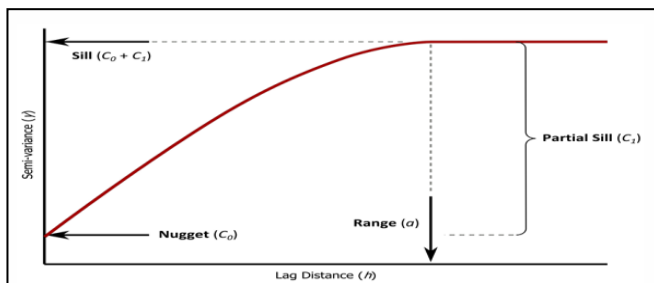


Figure 2. Components of a geostatistical variogram graph (Marwanza, 2023).

The third stage was the calculation of GEV and RE using several drill spacing scenarios ranging from 100 m to 3,000 m, with discretization predictions from point to block, block to block, and point to point based on the variogram model (Figure 3) (Heriawan et al., 2022).

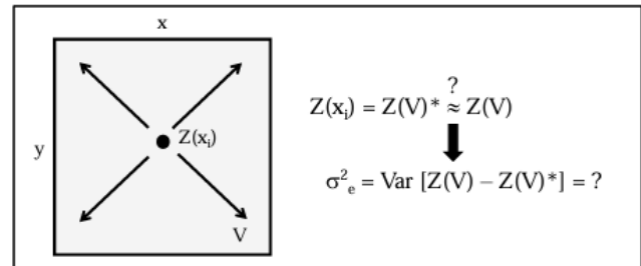


Figure 3. Principle of estimation variance from the extension of point $z(x_i)$ to volume V (Heriawan et al., 2022).

$$\sigma_e^2 = \gamma(S, V) - \gamma(V, V) - \gamma(S, S)$$

where $\gamma(S, V)$ is the average variogram value between drill points S and block volume V , $\gamma(V, V)$ is the average variogram value between points within block V and $\gamma(S, S)$ is the variogram value between drill points.

$$GEV = \frac{\sigma_e^2}{N}$$

where σ_e^2 is the estimation variance, which represents the variance of the estimated value obtained from the difference between the predicted block value and the estimated grid value. N is the number of blocks or grids in the evaluated area (Heriawan et al., 2022).

The resulting global estimation variance was then evaluated using relative error with the following equation:

$$Relative\ error = \frac{2 \times \text{standart deviation}}{Z} \times 100 \%$$

where the standard deviation is obtained from the square root of the estimation variance, and Z is the mean value of the analysed variable, in this case coal thickness and coal quality parameters (Heriawan et al., 2022).

The classification of resource confidence levels for drill spacing determination was based on Bertoli et al. (2013), where measured resources have RE < 10%, indicated resources have RE between 10% and 20%, and inferred resources have RE between 20% and 50%. A lower RE value indicates lower estimation uncertainty and higher geological confidence, whereas a higher RE value indicates greater uncertainty. In this study, the optimum drill spacing was determined by selecting the spacing that meets the required confidence level for

measured, indicated, and inferred coal resources. Therefore, this approach provides drill spacing recommendations based on quantitative variability.

Result and Discussion

Descriptive statistical analysis shows that Seam F has an average thickness of 3.19 m, with a median of 2.89 m and a mode of 4.43 m. The minimum thickness is 0.27 m, while the maximum thickness reaches 10.85 m. The positive skewness value indicates that the data distribution is slightly skewed to the right, meaning that several drill holes have thicker coal compared to the main data population. The coefficient of variation indicates that the overall thickness variability is low, with a value of 0.06. This means that, in general, Seam F can be considered relatively homogeneous.

For coal quality, Seam F also shows relatively low variability, with a CoV value of 0.05 for total sulfur. The total sulfur data have an average value of 1.10%, a median of 0.94%, and a mode of 0.83% (Table 1). The minimum sulfur value is 0.41%, while the maximum value reaches 2.53%. The standard deviation of 0.45% indicates that sulfur values are generally distributed close to the mean value. The positive skewness of sulfur indicates that some samples have higher sulfur values than the main data group, but overall variation remains low based on the CoV value. The calorific value of Seam F shows very low variability based on its coefficient variation of 0.01. The standard deviation of 150 kcal/kg indicates that calorific value has some variation, but the relative difference is small compared with the mean value. The skewness value of -0.5 indicates that the distribution is slightly skewed to the left, meaning that some data have lower calorific values than the main data population. The kurtosis value of 0.3 indicates that the calorific value distribution is relatively close to a normal distribution.

Seam	Parameter	Deskriptif Statistik						Standar deviasi	CoV
		Mean	Median	Modus	Skewness	Kurtosis			
F	Ketebalan	3.2	2.9	4.4	1.4	2.1	2.1	0.06	
F	Ash	7.4	6.7	6.9	2.6	9.8	2.8	0.04	
F	Nilai Kalori	3,133	3,148	3,262	-0.5	0.3	150	0.01	
F	Total Sulfur	1.1	0.9	0.8	0.8	0.4	0.4	0.05	

Table 1. Descriptive statistics of Seam F for quantity and quality

Based on the variability data of Seam F, calorific value has the lowest CoV of 0.01, indicating very low relative variability, whereas thickness and total sulfur show slightly higher CoV values of 0.06 and 0.05, respectively. This indicates that thickness and total sulfur are relatively more sensitive to spatial variation than calorific value. Therefore, the relationship between data variability and drill spacing can be interpreted as a positive linear relationship, meaning that higher

variability and lower spatial continuity require closer drill spacing.

Geostatistical analysis shows that descriptive statistics alone are not sufficient to explain the spatial characteristics of Seam F. For total sulfur, the nugget ratio of 11.7% indicates low local variation and good spatial continuity (Table 2). This means that sulfur values in Seam F are spatially consistent within the range of the variogram model. In contrast, calorific value has a nugget ratio of 60.8%, indicating stronger local variability. This result shows that calorific value is more sensitive to local changes between drill holes, even though its CoV is very low.

Seam	Parameter	Model Variogram			
		Sill	Range	Nugget	Nugget ratio
F	Ketebalan	3.2	2384	0.16	4.8%
F	Ash	6.8	338	0.28	4.0%
F	Nilai Kalori	8,422	907	13,048	60.8%
F	Total Sulfur	1.1	2116	0.15	11.7%

Table 2. Variogram parameter of Seam F for quantity and quality

The GEV and RE analyses show that estimation uncertainty increases as drill spacing becomes wider (Table 3).

Table 3. Calculation of Global Estimation Variance (GEV) and Relative Error (RE)

Parameter	Spasi Bor	S,V	V,V	S,S	Var Err	GEV	RE	RE %	
F - Ash	100	1.474	1.865	0	1.083	0.001	0.007	0.75%	
	250	3.069	3.871	0	2.267	0.005	0.022	2.17%	
	500	4.107	5.748	0	2.465	0.013	0.034	3.39%	
	750	6.224	6.384	0	6.063	0.055	0.071	7.09%	
	1000	6.575	6.637	0	6.514	0.092	0.092	9.18%	
	1500	6.830	6.834	0	6.826	0.139	0.113	11.28%	
	2000	6.850	6.850	0	6.850	0.190	0.132	13.18%	
F - CV	2500	6.850	6.850	0	6.850	0.248	0.151	15.07%	
	3000	6.850	6.850	0	6.850	0.314	0.169	16.95%	
	100	13047.805	13234.475	0	12861.135	7.287	0.002	0.17%	
	250	13825.006	14280.383	0	13369.628	30.299	0.004	0.35%	
	500	14266.532	15915.504	0	12617.559	64.339	0.005	0.51%	
	750	16268.942	17312.259	0	15225.625	138.022	0.008	0.75%	
	1000	17336.996	18360.339	0	16313.653	231.071	0.010	0.97%	
F - Ketebalan	1500	18972.882	19500.665	0	18445.100	376.216	0.012	1.24%	
	2000	19819.175	20023.285	0	19615.064	544.552	0.015	1.49%	
	2500	20174.109	20276.081	0	20072.136	727.825	0.017	1.72%	
	3000	20397.534	20441.583	0	20353.486	934.065	0.020	1.95%	
	F - Sulfur	100	0.229	0.255	0	0.202	0.000	0.007	0.67%
		250	0.341	0.408	0	0.274	0.001	0.019	1.95%
		500	0.403	0.660	0	0.147	0.002	0.029	2.86%
750		0.712	0.907	0	0.518	0.017	0.080	8.04%	
1000		0.895	1.146	0	0.643	0.036	0.120	11.95%	
1500		1.249	1.593	0	0.906	0.115	0.213	21.28%	
2000		1.585	1.980	0	1.189	0.270	0.325	32.51%	
F - Sulfur	2500	1.894	2.289	0	1.499	0.531	0.456	45.63%	
	3000	2.172	2.516	0	1.828	0.932	0.605	60.46%	
	100	0.175	0.186	0	0.164	0.000	0.018	1.75%	
	250	0.220	0.247	0	0.193	0.001	0.048	4.76%	
	500	0.245	0.349	0	0.142	0.002	0.082	8.17%	
	750	0.370	0.447	0	0.292	0.009	0.176	17.56%	
	1000	0.443	0.543	0	0.343	0.019	0.254	25.38%	
F - Sulfur	1500	0.584	0.716	0	0.452	0.058	0.437	43.67%	
	2000	0.715	0.860	0	0.571	0.129	0.655	65.47%	
	2500	0.833	0.965	0	0.702	0.248	0.907	90.71%	
	3000	0.935	1.038	0	0.832	0.424	1.185	118.54%	

Wider drill spacing produces higher RE values because fewer data points are available to represent the spatial variability of Seam F. Conversely, closer drill spacing produces lower RE values and higher estimation

confidence. Based on the RE analysis, the recommended optimum drill spacing is 550 m for measured resources, 825 m for indicated resources, and 1,650 m for inferred resources **Figure 3**.

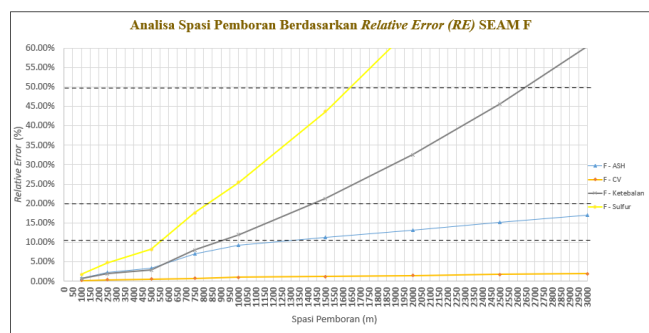


Figure 3. Drill Spacing Analysis Based on Relative Error Values seam F

Conclusion

Based on quantitative analysis, Seam F of the Muara Enim Formation in the Musi Banyuasin area generally has low variability in coal thickness and quality. This is indicated by relatively low coefficient variation (CoV) values, namely 0.06 for thickness, 0.04 for ash, 0.05 for total sulfur, and 0.01 for calorific value. These values indicate that Seam F is statistically relatively homogeneous, although local variation is still present in several parameters.

Variogram analysis shows that each parameter has different spatial continuity characteristics. Total sulfur has a nugget ratio of 11.7%, indicating low local variation and good spatial continuity. In contrast, calorific value has a nugget ratio of 60.8%, indicating stronger local variability compared with the other parameters. This shows that descriptive statistics alone are not sufficient to explain the spatial behavior of the data, and geostatistical analysis is required to understand the level of uncertainty between drill holes.

The results of global estimation variance (GEV) and relative error (RE) analyses show that estimation uncertainty increases as drill spacing becomes wider. Therefore, drill spacing that is too wide may reduce the confidence level of resource estimation, while overly close drill spacing may increase exploration costs without a proportional improvement in confidence. Based on the RE analysis, the recommended optimum drill spacing for Seam F is 550 m for measured resources, 825 m for indicated resources, and 1,650 m for inferred resources. This recommendation can be used as a basis for future exploration planning so that the drilling program becomes more effective, measurable, and cost-efficient.

The recommended spacing values were determined based on acceptable RE thresholds for each

resource classification category. In this study, the RE thresholds were set at $\leq 10\%$ for measured resources, $\leq 20\%$ for indicated resources, and $\leq 40\%$ for inferred resources. These thresholds were used to select the maximum drill spacing that still maintains an acceptable level of estimation uncertainty for each category. Therefore, the spacing values of 550 m, 825 m, and 1,650 m were not selected arbitrarily, but were derived from the GEV-RE scenarios where the RE values remain within the defined uncertainty limits. This approach is consistent with the geostatistical drillhole spacing analysis framework of (Bertoli et al., 2013), RE is used to quantify estimation uncertainty and support coal resource classification.

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