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Life of mine pit design optimization in anticline coal deposits based on break-even stripping ratio and slope stability analysis

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ABSTRACT

This study investigates how geological structure, economic limits, and slope stability can be integrated to optimize a Life of Mine (LoM) pit design in an anticline coal deposit. The objective is to determine an economically viable and technically safe pit design by evaluating pit shell alternatives using the Break-Even Stripping Ratio (BESR) and slope stability considerations. The study utilized secondary technical data from an existing mining project, including geological models, pit shell optimization results, mining cost parameters, geotechnical evaluations, mining constraints, and reserve estimates. No additional field investigation, numerical modeling, or recalculation of pit optimization and slope stability was performed. The anticline structure significantly influences seam geometry, overburden distribution, and stripping ratio characteristics. Pit shell evaluation was conducted using a BESR threshold of 5.8 bcm/ton. Among the evaluated alternatives, pit shell 4 was selected as the optimum design, generating approximately 61.51 million bcm of waste and 17.16 million tons of mineable coal, with an incremental stripping ratio of 5.04 and an accumulated stripping ratio of 3.58. Slope stability assessment indicated that several pit wall sections required geometry adjustments to meet safety requirements. The optimized LoM pit design resulted in a mineable coal reserve of 16.12 million tons. The findings demonstrate that integrating geological structure, BESR analysis, slope stability, and mining constraints is essential for producing a pit design that maximizes coal recovery while maintaining economic feasibility and operational safety in structurally complex coal deposits.

INTRODUCTION

Open-pit coal mining requires a pit design that is technically safe, economically feasible, and capable of maximizing mineable coal throughout the life of the mine. In long-term mine planning, the determination of the ultimate pit limit is a critical stage because it controls the amount of recoverable coal, the volume of overburden removal, the stripping ratio, the geometry of pit slopes, and the overall economic value of the mining operation. An improperly optimized pit design may result in excessive waste stripping, uneconomic pit expansion, coal losses, and increased operational risks. Therefore, pit design optimization should not

only aim to enlarge the mining boundary but also to ensure that each additional pit expansion remains technically justified and economically viable.

Recent studies have emphasized that ultimate pit limit optimization should integrate economic, technical, geotechnical, and environmental constraints rather than merely maximizing mineable material. The final pit boundary in open-pit coal mining is influenced by the interaction between economic benefit, ecological impact, slope geometry, and slope safety; therefore, pit optimization needs to be treated as a multi-constraint decision-making process rather than a single-objective maximization problem (Xu et al.,

2024). The inclusion of environmental and operational constraints in open-pit coal mine optimization may shift the ultimate pit boundary toward a more conservative but more sustainable configuration (Xu et al., 2023).

The complexity of pit design becomes more significant when coal deposits are affected by geological structures. One of the structural conditions that strongly influences open-pit coal mine planning is an anticline structure. In an anticline coal deposit, coal seams are folded upward, and the dip direction changes away from the fold axis. This condition causes variations in seam elevation, seam dip, overburden thickness, and coal continuity. As a result, the distribution of mineable coal becomes more complex compared with relatively flat or gently dipping deposits. Based on the technical dataset used in this study, the coal-bearing sequence is affected by an anticline structure, where the northern limb dips approximately 42° – 83° , while the southern limb dips approximately 36° – 47° . The anticline also plunges westward with a dip of approximately 12° – 24° , indicating that the seam geometry varies both laterally and vertically.

Such geological complexity directly affects the development of the pit limit. Coal seams located near the crest of an anticline may occur at relatively shallow depths, while seams along the limbs tend to become deeper and require higher overburden removal. This condition may increase the stripping ratio and reduce the economic value of pit expansion if the mining limit is not properly controlled. In this context, geological structure not only influences the physical distribution of coal but also affects the economic behavior of the pit. Variations in stripping ratio in open-pit coal mining can be driven by geological model uncertainty, mining sequence, operational losses, rehandling, pit redesign, and pit optimization, indicating that stripping ratio is not only an economic indicator but also a reflection of geological and operational complexity (Bakkula et al., 2025).

Break-Even Stripping Ratio (BESR) is one of the key parameters used to define the economic boundary of open-pit coal extraction. BESR represents the maximum allowable ratio between overburden removal and coal recovery under specific assumptions of coal price, mining cost, hauling cost, royalty, and other operational

expenditures. The BESR approach has been used to select an ultimate pit limit by comparing the incremental stripping ratio with the calculated break-even value, making it relevant for evaluating whether additional pit expansion remains economically justified (Suparno et al., 2025).

In the technical dataset analyzed in this paper, the BESR value used for pit shell evaluation is 5.8 bcm/ton. Several pit shell alternatives were generated, and the optimum shell was selected by comparing the incremental stripping ratio of each shell with the BESR value. Pit shell 4 was selected as the optimum pit shell because it generated approximately 61.51 million bcm of waste, 17.16 million tons of mineable coal, an incremental stripping ratio of 5.04, and an accumulated stripping ratio of 3.58. Although the next pit shell produced higher mineable coal tonnage, its incremental stripping ratio reached 6.50, which exceeded the BESR value. This condition shows that additional coal tonnage does not always indicate a better pit design when the additional waste removal has already passed the economic threshold.

However, economic feasibility alone is not sufficient to determine an applicable Life of Mine pit design. Slope stability remains a fundamental constraint in open-pit mine planning, particularly in structurally complex deposits. Anticline structures may create variations in bedding orientation, weak planes, fractured zones, and potential groundwater pathways that influence slope behavior. Slope stability analysis is a critical component in open-pit mine planning because weathering, material strength degradation, and geological discontinuities can significantly affect slope performance and mine safety (Liu et al., 2024). Slope stability problems in open-pit coal mines must be properly evaluated to reduce the potential for mine wall failure and to support safe mining operations (Francisco et al., 2024).

The slope stability evaluation in the analyzed dataset shows that several highwall sections were acceptable under the recommended geometry, while some sidewall and lowwall sections required modification. In particular, some sidewall sections required a reduction of the overall slope angle from 35° to 31° , while lowwall sections required a gentler overall slope angle of approximately 12° under saturated conditions. These geotechnical adjustments indicate that the optimum pit design is

not simply the pit shell with the largest amount of mineable coal, but the design that provides the best balance between mineable coal, overburden volume, economic stripping ratio, and slope stability.

The main problem addressed in this paper is how to optimize a Life of Mine pit design in an anticline coal deposit where seam geometry, stripping ratio, and slope stability are strongly interrelated. If pit expansion is carried out only to increase coal recovery without considering BESR and geotechnical constraints, the final pit may become uneconomic or unsafe. Production capacity and long-term mining range in open-pit coal mines are influenced by the relationship between working face length, annual advance rate, mining range, geological constraints, and economic feasibility (Liu et al., 2023). The dynamic optimization of open-pit coal mine boundaries also needs to consider coal price fluctuation because changes in economic assumptions can alter the technically and economically optimal mining boundary (Wang et al., 2024).

Based on this condition, this paper aims to present a Life of Mine pit design optimization for an anticline coal deposit based on Break-Even Stripping Ratio and slope stability analysis. The paper uses existing technical data from a previous thesis dataset, including geological models, pit shell optimization results, mining cost parameters, geotechnical recommendations, and coal reserve estimation. No additional data processing or new numerical modeling was conducted in this paper. The focus of this article is to synthesize and discuss how BESR and slope stability considerations can be integrated to determine an optimum ultimate pit design in a structurally controlled coal deposit.

The significance of this article lies in its attempt to demonstrate that pit optimization in anticline coal deposits must be interpreted beyond coal tonnage alone. In many open-pit coal mine planning studies, optimization is often associated with maximizing coal recovery or reducing the stripping ratio. However, in structurally controlled deposits, the pit limit must also reflect seam geometry, slope behavior, and operational constraints. Long-term open-pit mine planning increasingly requires the integration of economic and environmental considerations because conventional optimization approaches may not fully

represent the broader consequences of mine design decisions (Mirzehi et al., 2024). Open-pit mine planning also involves natural, geological, environmental, technical, economic, and social factors that should be considered within an integrated decision-making framework (Celebic et al., 2024).

This paper therefore contributes to practical mine planning by showing that the optimum pit shell is not necessarily the shell with the largest mineable coal tonnage. In the analyzed dataset, pit shell 5 produced more mineable coal than pit shell 4, but its incremental stripping ratio exceeded the BESR threshold. Consequently, pit shell 4 was more appropriate as the basis for the Life of Mine pit design. This finding confirms that the selection of an optimum pit shell should be based on the balance between additional coal recovery, additional waste removal, economic limits, and geotechnical stability.

Furthermore, the integration of slope stability analysis into pit optimization provides a more realistic basis for converting an economic pit shell into an applicable ultimate pit design. Slope angle and bench geometry optimization are essential to improve slope safety and operational performance in open-pit coal mining, especially when geological conditions and material properties strongly influence slope behavior (Alemayehu et al., 2025). In this study, the need to modify sidewall and lowwall geometry confirms that geotechnical recommendations are essential in translating an optimum pit shell into a safe and operationally feasible final pit design. Therefore, the integration of BESR and slope stability analysis can help ensure that Life of Mine pit design in anticline coal deposits remains economically viable, technically safe, and consistent with the actual geological condition of the deposit.

METHODS

This study applied a quantitative case-study approach based on secondary technical data from an existing Life of Mine pit optimization study on an anticline coal deposit. The method was designed to explain how an optimum pit design can be determined by integrating geological interpretation, Break-Even Stripping Ratio, pit shell evaluation, slope stability consideration, mining constraints, and reserve estimation. No additional field

investigation, drilling, laboratory testing, pit optimization rerun, slope stability recalculation, or reserve re-estimation was conducted in this paper. The analysis was limited to reorganizing and interpreting the available dataset so that the methodological process remains transparent and traceable for readers. A case-study approach is appropriate in mine planning research when the objective is to evaluate a specific technical condition using available geological, economic, operational, and geotechnical information from a defined mining area (Fathollahzadeh et al., 2021).

Study Area and Geological Setting

The object of this study is an open-pit coal deposit affected by an anticline structure in the South Sumatra Basin, Indonesia. The study did not involve human respondents; therefore, population and sampling in the social-research sense were not applied. The research subject was defined as the selected coal pit and its associated technical dataset, including geological models, exploration drilling data, geotechnical drilling data, topographic data, mining constraints, cost parameters, pit shell optimization results, slope stability recommendations, and coal reserve estimation. The coal-bearing sequence consists of several modeled seams, including Seam A, B1, B2, C1, C2, and D. The geological model was developed from 161 exploration drill holes, using a topographic model cell size of 10 m, geological model cell size of 10 m, interpolation search radius of 1,500 m, model extrapolation distance of 2,000 m, and finite element method interpolation for thickness, surface, and trend modeling.

Data Sources and Research Materials

Data collection in this paper was carried out through document-based data extraction from the previous technical thesis dataset. The extracted data included the geological setting of the anticline structure, seam geometry, pit shell optimization table, economic parameters, slope stability analysis results, mining constraints, and reserve classification. Since this paper did not conduct new numerical processing, the validity of the method depends on the clarity of the source dataset, the consistency of parameter interpretation, and the logical connection between the available results and the research objective. The use of existing technical datasets is acceptable in mine planning studies when the available data already contain sufficient

information to support pit design interpretation and decision-making under operational constraints (Nancel-Penard et al., 2025).

Geological Modeling and Structural Interpretation

The geological analysis was conducted by interpreting the relationship between anticline structure and pit design behavior. The anticline was identified from opposite bedding dips between the northern and southern limbs of the coal-bearing sequence. The northern limb dips approximately 42°–83°, while the southern limb dips approximately 36°–47°. The anticline also plunges westward with a dip of approximately 12°–24°. These geological conditions were used to explain variations in seam elevation, seam dip, coal continuity, overburden distribution, and stripping ratio. Geological structure was therefore treated as the first controlling factor in the interpretation of pit optimization results, because changes in bedding orientation may directly affect mineable coal geometry and pit wall configuration.

Pit Shell Optimization Approach

The pit optimization analysis was conducted using the same methodological basis as the thesis, namely, pit shell evaluation through an incremental pit expansion approach and economic stripping ratio control. The available pit shell alternatives were examined by comparing waste volume, mineable coal tonnage, incremental stripping ratio, and accumulated stripping ratio.

The optimum shell was selected based on the relationship between incremental stripping ratio and Break-Even Stripping Ratio, rather than by selecting the shell with the highest coal tonnage. This approach is important because practical open-pit phase design should not only pursue maximum material extraction but also satisfy operational, geometric, and production-related constraints (Nancel-Penard et al., 2025).

Break-Even Stripping Ratio Analysis

Stripping Ratio was used to describe the relationship between overburden volume and coal tonnage. In this study, the stripping ratio values were adopted from the existing pit shell optimization results and were not recalculated. The basic stripping ratio concept can be expressed as follows:

$$SR = \frac{\text{Waste Volume (bcm)}}{\text{Coal Tonnage (ton)}}$$

Break-Even Stripping Ratio was used as the economic threshold for selecting the optimum pit shell. In this paper, the BESR value was adopted directly from the thesis dataset, where the economic parameters included coal price, coal mining cost, overburden removal cost, hauling cost, port handling cost, royalty, overhead and administration, environmental rehabilitation cost, community development cost, contingency, dead rent, and capital expenditure. The BESR value used for pit shell evaluation was 5.8 bcm/ton. The conceptual formula used to explain BESR in this study is:

$$\text{BESR} = \frac{\text{Coal Price-Total Coal Cost}}{\text{Waste Removal Cost}}$$

The optimum pit shell was then determined by comparing the incremental stripping ratio of each pit shell with the BESR threshold. Incremental stripping ratio was used because it represents the additional waste that must be removed for each additional coal tonnage obtained when the pit is expanded from one shell to the next. The incremental stripping ratio can be expressed as follows:

$$\text{Incremental SR} = \frac{\Delta \text{Waste Volume}}{\Delta \text{Coal Tonnage}}$$

Based on the available pit shell optimization results, pit shell 4 was selected as the optimum shell because it produced approximately 61.51 million bcm of waste, 17.16 million tons of mineable coal, an incremental stripping ratio of 5.04, and an accumulated stripping ratio of 3.58. Although pit shell 5 produced a higher mineable coal tonnage of approximately 18.74 million tons, its incremental stripping ratio increased to 6.50, exceeding the BESR value of 5.8 bcm/ton. This comparison shows that pit shell 4 provided a better balance between additional coal recovery and additional waste removal.

Slope Stability Assessment

Slope stability analysis was incorporated as a geotechnical constraint in translating the selected economic pit shell into a final Life of Mine pit design. The slope stability data were adopted from the existing geotechnical evaluation and included highwall, sidewall, and lowwall sections under static and pseudo-static conditions. The evaluation considered overall slope height, overall slope angle, factor of safety, probability of failure, saturated

material condition, groundwater assumption, structural influence, and seismic loading. The stability condition was interpreted using the factor of safety concept, which compares resisting forces against driving forces along a potential failure surface. The basic form of the factor of safety is:

$$\text{FoS} = \frac{\text{Resisting Force}}{\text{Driving Force}}$$

The use of factor of safety and probability of failure is relevant in open-pit slope assessment because deterministic stability analysis alone may not fully represent the variability of rock mass properties, discontinuities, groundwater conditions, and uncertainty in geotechnical parameters (Abdulai and Sharifzadeh, 2021). The interpretation of slope stability in this study, therefore, did not attempt to generate new stability values but used the available factor of safety and probability of failure results as design constraints for evaluating the applicability of the selected pit shell.

The geotechnical dataset showed that several highwall sections were acceptable with overall slope angles ranging from 26° to 28°. However, some sidewall sections with an initial overall slope angle of 35° were classified as not acceptable and required a reduction of the overall slope angle to 31°. The lowwall sections were also found to be critical under saturated conditions and required a gentler overall slope angle of approximately 12°. These results indicate that the selected pit shell could not be directly converted into a final pit design without geotechnical adjustment. The selection of an optimal overall slope angle in open-pit mines should consider safety, productivity, and mining cost because slope flattening may improve stability but can also increase waste removal and affect the economic value of the pit (Abdellah et al., 2022).

Mining Constraints and Design Parameters

Mining constraints were also considered in the methodological interpretation of the ultimate pit design. The constraints included mining boundary offsets, settlement areas, powerline networks, high-voltage transmission lines, public roads, pipeline infrastructure, and depth limitation. The original dataset applied a 50 m offset from the mining concession boundary, 150 m offsets from several infrastructure constraints, and a maximum depth limit of -100 m from the surface. These constraints

were treated as spatial and operational limitations that controlled the final pit geometry after the economic and geotechnical evaluation had been considered. Open-pit mine planning should account for operational space, geometric requirements, mining capacity, and safe working conditions because an optimized boundary that cannot be practically mined may not be applicable in real operations (Jelvez et al., 2023).

Reserve Estimation Method

Reserve estimation was interpreted using the modifying factors already available in the thesis dataset. These factors included roof and floor mining loss of 0.2 m, roof and floor dilution of 0.1 m, minimum mineable coal thickness of 0.3 m, minimum parting thickness of 0.1 m, and global recovery of 98%. The reserve output was used to evaluate the final contribution of the selected ultimate pit design to mineable coal. The final reserve obtained from the optimized Life of Mine pit design was 16.12 million tons, consisting of 16.11 million tons of proved reserve and 0.01 million tons of probable reserve.

Data Analysis Framework

The data analysis was carried out in four sequential stages. The first stage was geological interpretation, which examined how the anticline structure influenced seam dip, seam elevation, coal continuity, and potential pit geometry. The second stage was economic interpretation, which evaluated the relationship between pit shell alternatives, incremental stripping ratio, and BESR. The third stage was geotechnical interpretation, which assessed how slope stability recommendations modified the selected pit shell into a safer ultimate pit design. The fourth stage was reserve interpretation, which connected the final pit design with the reported reserve outcome. These stages were integrated to answer the research problem: how BESR and slope stability analysis can be used together to determine an optimum Life of Mine pit design in an anticline coal deposit.

This methodological structure was selected because the paper aims to synthesize existing technical results rather than produce new numerical simulations. The method allows the study to remain transparent by clearly stating what data were used, how the data were interpreted, and which limitations applied. The main limitation is that the results depend on the accuracy and completeness of

the original geological model, economic assumptions, pit shell optimization, and geotechnical evaluation. Nevertheless, the method remains valid for a journal article because it provides a structured interpretation of a real mine-planning dataset and explains the technical basis for selecting an optimum Life of Mine pit design. Long-term open-pit mine planning increasingly requires decision-support logic that integrates geological uncertainty, optimization constraints, computational efficiency, and practical mine design considerations into a coherent planning framework (Rahimi, 2025).

RESULTS AND DISCUSSION

Geological Control of Anticline Structure

The optimization of Life of Mine pit design in an anticline coal deposit is controlled by the interaction between geological structure, waste volume, mineable coal, stripping ratio, economic limit, slope stability, mining constraints, and reserve distribution. In this study, the anticline structure acts as the primary geological control because it influences seam dip, seam elevation, seam continuity, and overburden thickness. The northern limb of the anticline dips approximately 42° – 83° , while the southern limb dips approximately 36° – 47° . The anticline also plunges westward with a dip of approximately 12° – 24° . These structural conditions cause coal seams to occur at different depths and orientations, which directly affect the development of pit geometry and the economic behavior of each pit shell.

The influence of anticline structure on pit optimization is also supported by previous studies on open-pit coal mines developed in structurally complex areas. In a coal deposit affected by a steep anticline, mining and dumping development cannot be treated in the same way as in non-anticline areas because the geological condition changes significantly across the folded zone (Azarfar, 2019). This means that anticline geometry may alter mining direction, overburden distribution, pit expansion strategy, and dumping coordination. Therefore, the selection of the optimum pit shell in an anticline coal deposit must consider the spatial relationship between seam position, fold geometry, and the economic limit of overburden removal (Zhao et al., 2022).

Based on this geological condition, the pit shell evaluation was interpreted by examining how pit expansion affects both waste volume and mineable coal. The relationship between these variables is important because anticline geometry may cause coal seams to become deeper toward the limb areas, resulting in a rapid increase in overburden removal. Therefore, the next stage of analysis focuses on the relationship between pit shell expansion, waste volume, mineable coal, and stripping ratio.

The geological model indicates that the coal-bearing sequence consists of several seams,

including Seam A, B1, B2, C1, C2, and D. Among these seams, Seam A is the dominant seam in terms of reserve contribution. This condition is important because the continuity, depth, and dip variation of Seam A strongly influence the shape of the ultimate pit. In an anticline-controlled deposit, coal located near the crest of the anticline may be shallower and more favorable for mining, whereas coal located along the limbs tends to be deeper and requires greater overburden removal. Therefore, the geological structure has an indirect but significant influence on the stripping ratio and economic pit limit (Qing, 2021).

Table 1. Geological control of anticline structure on pit design

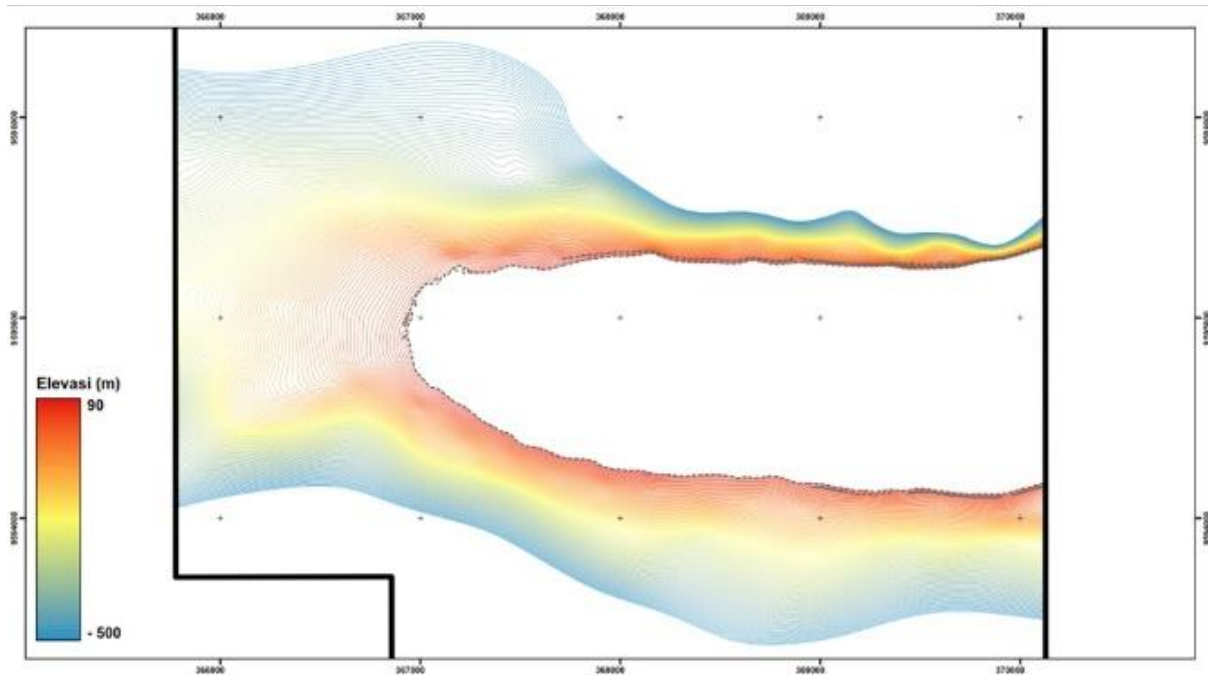
Geological Aspect	Observed Condition	Influence on Pit Design
Structural setting	Anticline-controlled coal deposit	Creates variable seam elevation and dip direction
Northern limb dip	Approximately 42°–83°	Produces steeper bedding orientation and potential slope sensitivity
Southern limb dip	Approximately 36°–47°	Controls pit wall geometry and coal exposure along the limb
Westward plunge	Approximately 12°–24°	Causes lateral and vertical changes in seam position
Main coal seam	Seam A	Dominates reserve distribution and controls pit development
Mining implication	Variable overburden thickness	Influences stripping ratio and pit shell selection

Source: Authors' processing of research data (2026)

The data in Table 1 show that the anticline structure is not only a geological feature, but also a controlling variable in mine planning. The change in seam dip affects the depth and spatial position of coal, while the variation in coal depth affects overburden volume. This relationship means that geological structure influences the stripping ratio through its control on overburden distribution. Consequently, pit optimization in this study cannot be assessed only from mineable coal tonnage,

because the additional coal obtained from pit expansion may require disproportionately higher waste removal.

The structural control of Seam A can be observed from the floor structure contour map, which shows significant variation in seam elevation across the study area. This elevation variation reflects the influence of anticline geometry on coal depth, overburden distribution, and potential pit development (Figure 1).



Source: Authors' processing of research data (2026)

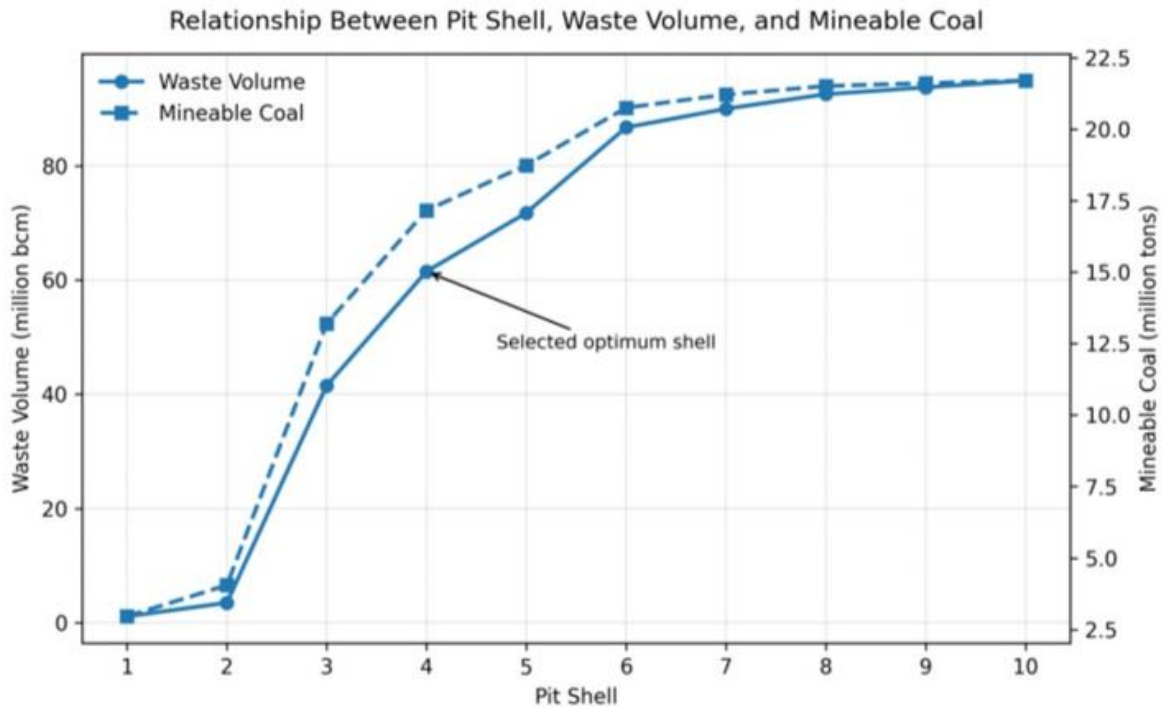
Figure 1. Structure contour map of seam A floor elevation coal reserve distribution by seam

As shown in Figure 1, the floor elevation of Seam A varies laterally across the study area. The higher-elevation zones represent relatively shallower coal positions, while the lower-elevation zones indicate deeper coal occurrence. This variation is important because pit expansion toward deeper seam positions generally requires higher overburden removal. Therefore, the Seam A structure contour map supports the interpretation that anticline-controlled seam geometry directly influences stripping ratio behavior and the economic limit of pit expansion.

Pit Shell Optimization Result

The relationship between pit shell, waste volume, and mineable coal is shown in Figure 2. The graph indicates that both waste volume and

mineable coal increase as the pit shell expands. However, the rate of increase is not proportional. From pit shell 3 to pit shell 4, mineable coal increased from 13,20 million tons to 17,16 million tons, while waste volume increased from 41,52 million bcm to 61,51 million bcm. This means that an additional 3,96 million tons of coal required an additional 19,99 million bcm of waste removal. Meanwhile, from pit shell 4 to pit shell 5, mineable coal increased only from 17,16 million tons to 18,74 million tons, while waste volume increased from 61,51 million bcm to 71,78 million bcm. This means that only 1,58 million tons of additional coal required 10,27 million bcm of additional waste removal.



Source: Authors' processing of research data (2026)

Figure 2. Relationship between Pit Shell, Waste Volume, and Mineable Coal Graph

The interpretation of Figure 2 shows a clear relationship between pit expansion and mining efficiency. The figure shows that pit expansion increases both waste volume and mineable coal. However, after pit shell 4, the additional mineable coal becomes less proportional to the additional waste volume, indicating declining efficiency of pit expansion. At early pit shells, the increase in waste volume is still followed by a relatively significant increase in coal tonnage. However, after pit shell 4, the additional waste required to obtain additional

coal becomes less efficient. This trend reflects the influence of anticline geometry, where pit expansion toward deeper limb areas tends to increase overburden removal faster than coal recovery. Therefore, waste volume acts as a limiting variable, while mineable coal acts as the benefit variable. The optimum pit shell is achieved when the benefit of additional coal is still economically higher than the burden of additional waste removal (Hart, 2020).

Table 2. Comparison of waste volume, mineable coal, and stripping ratio for selected pit shells

Pit Shell	Waste Volume (million bcm)	Mineable Coal (million tons)	Incremental SR (bcm/ton)	Accumulated SR (bcm/ton)	Interpretation
3	41.52	13.20	4,16	3,15	Economically acceptable
4	61.51	17.6	5,04	3,58	Optimum shell
5	71.78	18.74	6,50	3,83	Exceeds BESR
6	86.75	20.75	7,47	4,18	Less economic for further expansion

Source: Authors' processing of research data (2026)

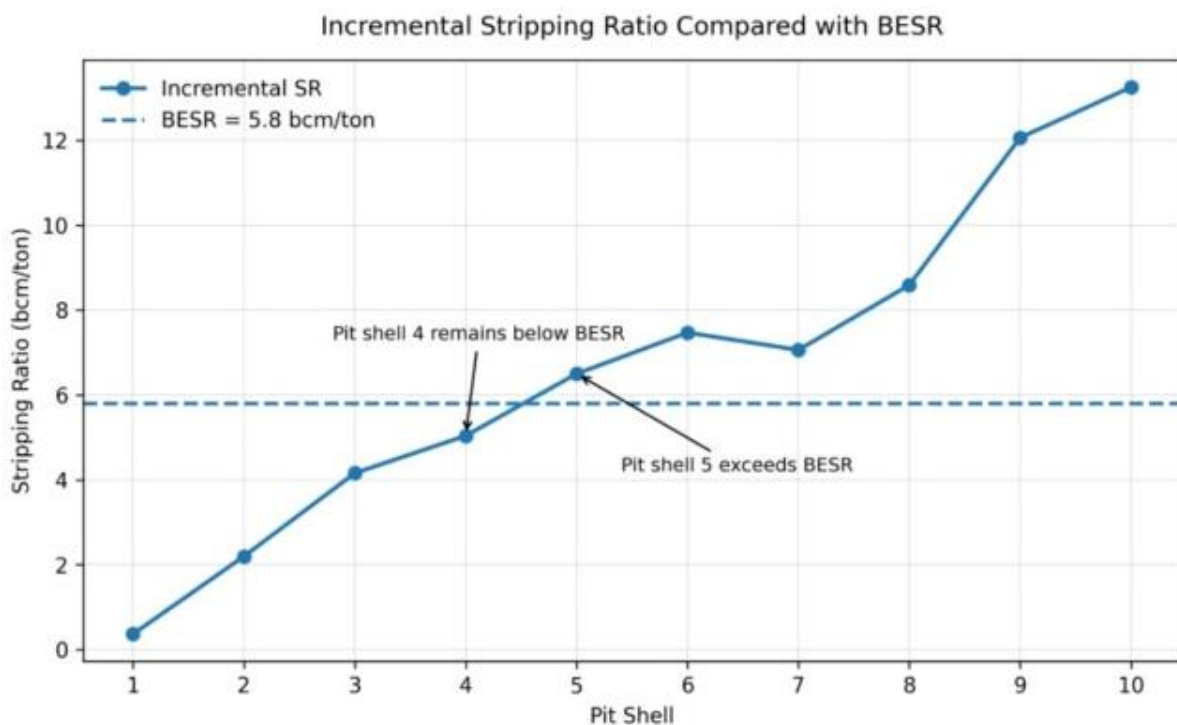
Table 2 confirms that pit shell 4 provides the most balanced result between waste volume and mineable coal. Although pit shell 5 and pit shell 6 produce higher coal tonnage, their incremental stripping ratios exceed the Break-Even Stripping Ratio threshold. This shows that a larger pit shell

does not automatically represent a better design. The relationship between mineable coal and waste volume must be evaluated through the incremental stripping ratio because this parameter measures the economic consequence of each additional pit expansion (Cao et al., 2023).

The relationship between pit shell expansion, waste volume, and mineable coal reflects the basic economic behavior of open-pit mining. As the pit shell becomes larger, the amount of recoverable coal may increase, but the additional overburden removal may also increase at a faster rate. This condition confirms that pit optimization cannot be evaluated only from total coal tonnage, because the economic value of additional coal depends on the waste burden required to expose it. In open-pit coal mining, the average stripping ratio is one of the most important parameters affecting the mining boundary, construction pace, economic benefit, resource utilization, production quantity, and product quality (Lv et al., 2025).

BESR-Based Economic Evaluation

The Break-Even Stripping Ratio used in this study was 5,8 bcm/ton. This value represents the maximum allowable stripping ratio at which additional coal extraction remains economically feasible. Figure 3 compares the incremental stripping ratio of each pit shell against the BESR threshold. Pit shell 1 to pit shell 4 remain below the BESR value, while pit shell 5 and subsequent shells exceed the threshold. Pit shell 4 has an incremental stripping ratio of 5.04, which is still below the BESR value. In contrast, pit shell 5 has an incremental stripping ratio of 6,50, indicating that the additional expansion from pit shell 4 to pit shell 5 is no longer economically justified.



Source: Authors' processing of research data (2026)

Figure 3. Incremental Stripping Ratio Compared with Break-Even Stripping Ratio

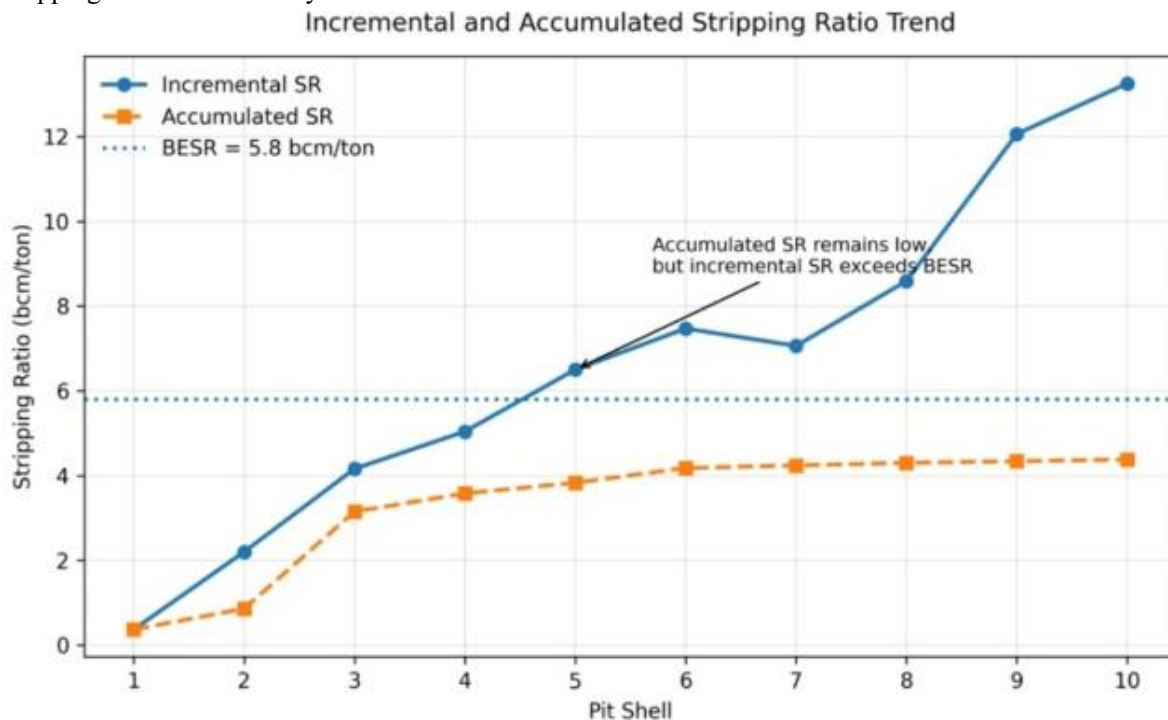
Figure 3 is the most important evidence for selecting pit shell 4 as the optimum shell. The figure shows that pit shell 4 is the last shell with an incremental stripping ratio below the BESR threshold of 5,8 bcm/ton. Pit shell 5 exceeds the threshold and is therefore not selected as the optimum pit shell. The relationship between incremental stripping ratio and BESR shows the economic limit of pit expansion. Incremental stripping ratio represents the additional waste burden required to obtain additional coal, while BESR represents the maximum economic tolerance for that burden. When the incremental stripping

ratio is lower than BESR, the additional pit expansion is still economically acceptable. When the incremental stripping ratio exceeds BESR, the additional coal is no longer sufficient to compensate for the additional waste removal cost. Based on this relationship, pit shell 4 is the optimum shell because it is the final shell that remains below the BESR threshold.

The comparison between the incremental stripping ratio and the accumulated stripping ratio is shown in Figure 4. This comparison is important because accumulated stripping ratio may give a different impression from incremental stripping

ratio. Pit shell 5 has an accumulated stripping ratio of 3,83, which is still below BESR. However, its incremental stripping ratio is 6,50, which already exceeds BESR. This indicates that the accumulated stripping ratio alone may not be sufficient to

determine the optimum pit shell because it averages the overall pit performance and may hide the declining economic efficiency of marginal expansion.



Source: Authors' processing of research data (2026)
Figure 4. Incremental and accumulated SR trend

The interpretation of Figure 4 shows that the incremental stripping ratio is a more appropriate parameter for pit shell selection than the accumulated stripping ratio. The figure shows that the accumulated stripping ratio remains relatively low, while the incremental stripping ratio increases sharply after pit shell 4. This indicates that the incremental stripping ratio is more sensitive to evaluating the economic feasibility of additional pit expansion. Accumulated stripping ratio describes the average relationship between total waste and total coal from the beginning of pit development. Meanwhile, the incremental stripping ratio describes the marginal relationship between additional waste and additional coal from one shell to the next. In this study, the accumulated stripping ratio remains below BESR even after pit shell 5, but the incremental stripping ratio has already exceeded BESR. This means that the overall pit may still appear economic, but the next expansion step is already uneconomic. Therefore, the selection of pit shell 4 is technically stronger because it considers

marginal economic behavior rather than total average performance.

The comparison between the incremental stripping ratio and the accumulated stripping ratio is important because both parameters describe different economic meanings. Accumulated stripping ratio shows the average condition of the whole pit, while incremental stripping ratio shows the economic consequence of expanding from one pit shell to the next. In pit shell selection, the incremental value is more sensitive for identifying the point where additional expansion begins to lose economic justification. This supports the interpretation that a pit shell with higher coal tonnage should not automatically be selected when its incremental stripping ratio has already exceeded the economic threshold. The use of stripping ratio as a control parameter has also been applied in coal reserve and pit design studies, where pit design feasibility is evaluated by comparing waste volume, coal tonnage, and allowable stripping ratio (Sakdillah & Trides, 2021).

Slope Stability Constraints on Ultimate Pit Design

The slope stability evaluation indicates that not all pit wall sectors have the same geotechnical response, as shown in Table 3. The highwall sections generally show acceptable stability, with static FK values ranging from 1.79 to 1.84 and pseudo-static FK values ranging from 1,48 to 1,67. These values indicate that the highwall geometry can be maintained within the evaluated overall

slope angle range of 26°–28°. In contrast, the sidewall sector shows mixed stability conditions. As presented in Table 3, Sect_SW_01 remains acceptable, while Sect_SW_02 and Sect_SW_03 are classified as not acceptable, with pseudo-static FK values of 1,02 and 1,04, respectively. The high PoF value of 42,1% in Sect_SW_02 indicates that the sidewall sector requires slope flattening before being incorporated into the final Life of Mine pit design.

Table 3. Summary of overall slope stability evaluation for highwall, sidewall, and lowwall sectors

Slope Sector	Section	Overall Slope Height (m)	Overall Slope Angle (°)	Static FK	Pseudo-static FK	PoF Pseudo-static (%)	Geotechnical Status
Highwall	Sect_HW_01	76	26	1,79	1,48	0	Acceptable
Highwall	Sect_HW_02	80	28	1,83	1,67	0,9	Acceptable
Highwall	Sect_HW_03	98	28	1,84	1,52	0	Acceptable
Sidewall	Sect_SW_01	77	35	1,51	1,23	0	Acceptable
Sidewall	Sect_SW_02	98	35	1,15	1,02	4,21	Not Acceptable
Sidewall	Sect_SW_03	100	35	1,25	1,04	7,30	Not Acceptable
Lowwall	Sect_LW_01	78	14	1,12	0,98	52	Not Acceptable
Lowwall	Sect_LW_02	80	17	0,99	0,78	100	Not Acceptable

Source: Authors' processing of research data (2026)

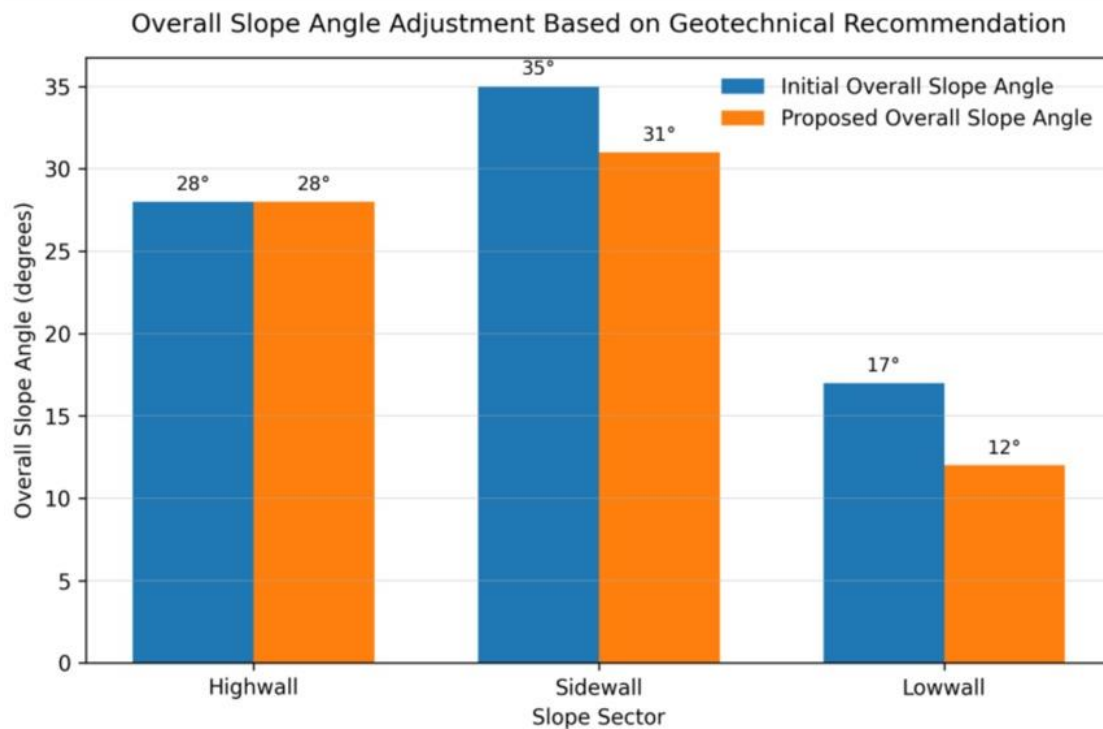
The lowwall sector represents the most critical slope condition in the evaluated pit design. Based on Table 3, Sect_LW_01 and Sect_LW_02 are both classified as not acceptable under saturated conditions, with pseudo-static FK values of 0,98 and 0,78 and PoF values of 52% and 100%, respectively. This condition indicates that the low wall is highly sensitive to groundwater or saturation effects. In an anticline coal deposit, this sensitivity is technically important because the lowwall geometry is closely related to bedding orientation and seam dip. Therefore, the low wall cannot be treated only as a geometric boundary of the pit, but must be interpreted as a geotechnical control that may limit the final pit configuration.

The results in Table 3 also confirm that the selected economic pit shell cannot be directly converted into an ultimate pit design without geotechnical modification. Although pit shell 4 is economically acceptable based on the BESR criterion, the final pit geometry must still accommodate slope stability requirements. This is

why the sidewall angle needs to be reduced from 35° to 31°, while the lowwall requires a gentler overall slope angle of approximately 12°. Therefore, the relationship between BESR and slope stability is complementary: BESR defines the economic boundary of pit expansion, while slope stability defines the safe engineering boundary of the final pit design.

The economic interpretation above cannot stand alone without geotechnical evaluation. The selected pit shell must be translated into a safe and applicable ultimate pit design. The slope stability evaluation shows that highwall, sidewall, and lowwall sectors have different stability conditions. Several highwall sections were acceptable with overall slope angles ranging from 26° to 28°. However, some sidewall sections with an initial overall slope angle of 35° were not acceptable and required flattening to 31°. The lowwall sections were also critical under saturated conditions, where the initial overall slope angles of 14°–17° required adjustment to approximately 12°. The comparison

between the initial and proposed overall slope angles is illustrated in Figure 5 and summarized in Table 4.



Source: Authors' processing of research data (2026)

Figure 5. Overall Slope angle adjustment based on geotechnical recommendation

Table 4. Slope angle adjustment based on geotechnical recommendation

Slope Sector	Initial Overall Slope Angle	Proposed Overall Slope Angle	Geotechnical Interpretation
Highwall	26°–28°	26°–28°	Acceptable; no major adjustment required
Sidewall	35°	31°	Flattening required to improve stability
Lowwall	14°–17°	12°	Flattening is required under saturated conditions

Source: Authors' processing of research data (2026)

The low wall sector is particularly sensitive in structurally controlled coal deposits because its geometry may be strongly influenced by bedding orientation and groundwater conditions. When bedding planes, weathered material, or saturated zones are present, slope resistance may decrease, and the probability of failure may increase. Previous research on open-pit slope failure has shown that geological conditions, rainfall, mining disturbance, and slope geometry interact with each other in controlling the landslide mechanism. This supports the interpretation that the proposed flattening of the low wall to approximately 12° is not merely a conservative design choice but a geotechnical response to structural and hydrogeological risk (Chen et al., 2023).

The relationship between slope stability and pit optimization is significant because geotechnical adjustment may influence the final pit geometry, waste volume, and recoverable coal. A steeper slope may reduce waste removal and improve economic performance, but it may increase the risk of slope failure. Conversely, a flatter slope improves stability but may increase waste volume or reduce access to marginal coal (Kumar, 2023). In this study, the sidewall and lowwall sectors required slope flattening, which means that the economic pit shell had to be adjusted to meet safety requirements. This confirms that the optimum Life of Mine pit design is not only determined by BESR, but also by geotechnical feasibility.

The lowwall adjustment is particularly important in an anticline coal deposit because

lowwall geometry is closely related to bedding orientation. When the slope follows or intersects bedding planes under saturated conditions, the potential for instability may increase. Therefore, the requirement to reduce the low wall angle to approximately 12° shows that the structural orientation of coal-bearing strata can directly influence slope design. In this case, anticline structure affects slope stability through bedding dip, while slope stability affects pit design through allowable slope geometry.

The need to adjust the sidewall and low wall slope angles indicates that economic optimization must be constrained by geotechnical stability. In open-pit coal mines, bedding planes are important discontinuities because they may act as potential slip surfaces, especially when the slope dip direction is relatively parallel to the bedding orientation. This condition is highly relevant in folded coal deposits because bedding orientation changes across the anticline limbs. Therefore, slope stability in an anticline coal deposit should not be interpreted only from the overall slope angle, but also from the relationship between slope face orientation, bedding dip, groundwater condition, and potential failure mechanism (Akbar et al., 2020).

Mining Constraints on Final Pit Geometry

Mining constraints further influence the final ultimate pit design. The optimization process considered mining boundary offsets, settlement areas, powerline networks, high-voltage transmission lines, public roads, pipeline infrastructure, and depth limitations. The dataset applied a 50 m offset from the mining boundary, 150 m offsets from several infrastructure constraints, and a maximum depth limit of -100 m from the surface. These constraints limit the possible expansion of the pit and ensure that the final design remains compatible with spatial, operational, and safety requirements.

Table 5 shows that the ultimate pit design is not only influenced by geological and economic variables but also by spatial constraints. These constraints act as boundary conditions that restrict how far the pit can expand horizontally and vertically. The relationship between mining constraints and pit optimization is direct: even when a coal block is economically attractive and geotechnically feasible, it may still be excluded from the final pit if it violates spatial constraints (Balci & Kumral, 2025). Therefore, mining constraints function as external limiting variables in the final pit design.

Table 5. Mining constraints considered in ultimate pit design

Constraint Type	Applied Limitation	Influence on Pit Design
Mining boundary	50 m offset	Limits pit expansion near the concession boundary
Settlement area	150 m offset	Prevents pit encroachment toward the residential area
Powerline network	150 m offset	Controls pit boundary near power infrastructure
High-voltage transmission line	150 m offset	Restricts pit expansion near the SUTT corridor
Public road	150 m offset	Maintains safe distance from road infrastructure
Pipeline infrastructure	150 m offset	Controls pit limit near pipeline corridor
Depth limitation	-100 m from surface	Limits vertical pit development

Source: Authors' processing of research data (2026)

Mining constraints act as external boundary conditions that may limit the final pit geometry even when a coal zone is economically attractive and geotechnically mineable (Deressa et al., 2025). In practical open-pit planning, pit design must consider not only coal and waste distribution but also infrastructure, access, safety distance, working space, and operational continuity. A pit design that ignores these practical constraints may appear optimal in the model but may not be applicable in real mining operations. Studies on pit design based

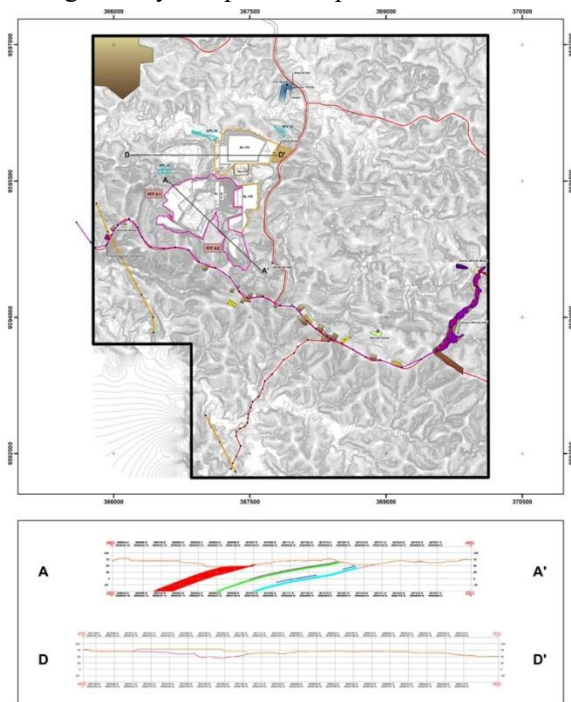
on production and operational targets show that deviations in overburden removal, coal production, and stripping ratio can occur when the design is not aligned with operational constraints and scheduling requirements (Ismail et al., 2025).

Ultimate Pit Design and Reserve Estimation

After integrating geological interpretation, BESR-based pit shell selection, slope stability adjustment, and mining constraints, pit shell 4 was translated into the ultimate Life of Mine pit design. The final design was not simply the direct output of

pit shell optimization, but the result of engineering adjustment. The pit shell provided the economic envelope, slope stability provided the geotechnical limitation, mining constraints provided the spatial boundary, and the anticline structure provided the geological control. This integrated process produced a final design that is more realistic for long-term mining operations.

The spatial relationship between the pit area, topographic condition, and geological section lines is presented in Figure 5. This map provides a visual basis for understanding how the selected pit design is positioned within the mining area and how cross-sectional interpretation supports the evaluation of seam geometry and pit development.



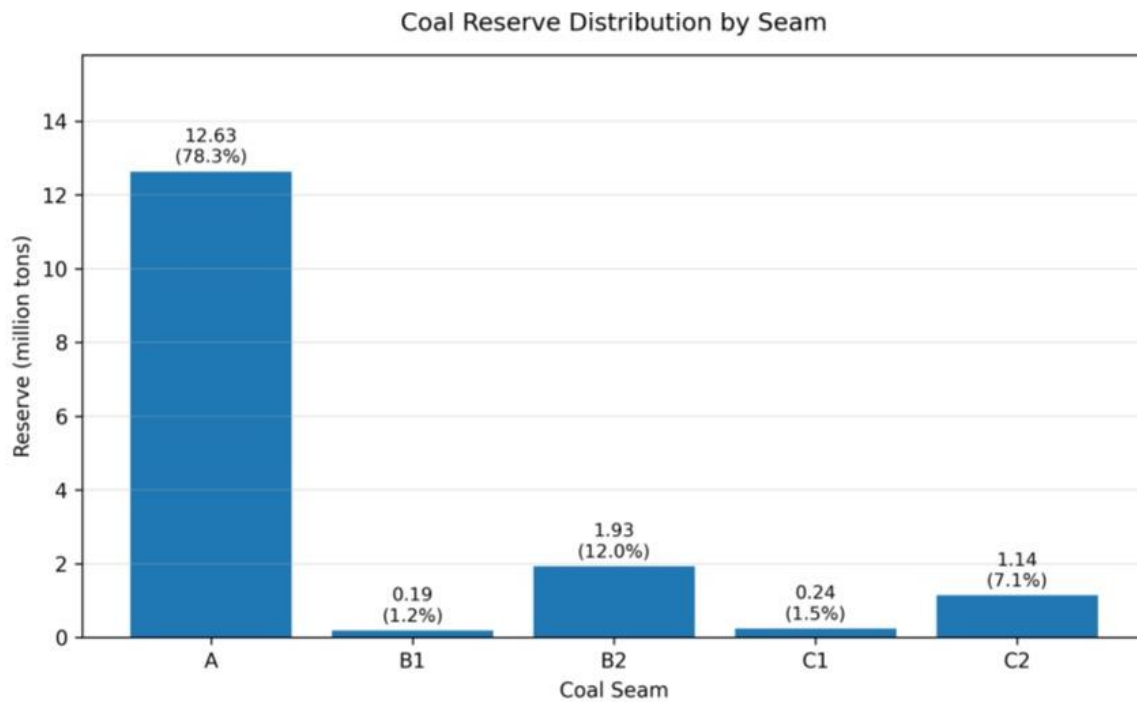
Source: Authors' processing of research data (2026)

Figure 6. Pit layout and mining stage map with geological cross-section lines

Figure 6 shows that the pit design is positioned within a topographically variable area and is supported by geological cross-section lines. This spatial information is important because pit optimization is not only controlled by numerical parameters such as BESR and stripping ratio, but also by the physical position of the pit relative to terrain, seam exposure, and geological section interpretation. Therefore, the map strengthens the argument that the final Life of Mine pit design is the result of integrated geological, economic, geotechnical, and spatial considerations.

The reserve estimation results show that the optimized Life of Mine pit design produced a total coal reserve of 16.12 million tons. This reserve consists of 16.11 million tons of proved reserves and 0.01 million tons of probable reserves. The reserve estimation considered modifying factors, including roof and floor mining loss of 0,2 m, roof and floor dilution of 0.1 m, minimum mineable coal thickness of 0,3 m, minimum parting thickness of 0.1 m, and global recovery of 98%.

The reserve distribution by seam is shown in Figure 7 and Table 6. Seam A is the dominant reserve contributor, with 12,63 million tons out of the total 16,12 million tons. This represents approximately 78% of the total reserve. Seam B2 contributes 1.93 million tons, Seam C2 contributes 1,14 million tons, Seam C1 contributes 0,24 million tons, and Seam B1 contributes 0,19 million tons.



Source: Authors' processing of research data (2026)

Figure 7. Coal reserve distribution by seam

Table 6. Coal reserve distribution by seam

Seam	Reserve (million tons)	Percentage of Total Reserve	Interpretation
A	12,63	78,4%	Main reserve contributor
B1	0,19	1,2%	Minor contribution
B2	1,93	12,0%	Secondary contribution
C1	0,24	1,5%	Minor contribution
C2	1,14	7,1%	Supporting contribution
Total	16,12	100%	Final optimized reserve

Source: Authors' processing of research data (2026)

Figure 7 and Table 6 show that the success of the Life of Mine pit design is strongly dependent on Seam A. Because Seam A contributes the majority of the reserve, the position, dip, and continuity of this seam become dominant factors in determining the final pit geometry. This relationship is important in an anticline coal deposit because the geometry of Seam A is structurally controlled. If Seam A becomes deeper toward the anticline limbs, the stripping ratio may increase. If Seam A remains accessible near the anticline crest or economically favorable zone, the pit design becomes more efficient. Therefore, reserve distribution is directly related to geological structure and indirectly related to economic pit optimization.

The dominance of Seam A in the reserve distribution indicates that the final pit design is controlled by the seam that contributes the largest mineable coal volume. In this condition, the

geometry and continuity of the dominant seam become more influential than the presence of minor seams. If the dominant seam becomes deeper or structurally complicated toward the anticline limbs, the stripping ratio may increase and reduce the economic value of further pit expansion. This interpretation is consistent with coal mine planning principles, where seam thickness, continuity, depth, and structural position directly affect reserve estimation, production strategy, and the life-of-mine plan (Wen et al., 2026).

Integrated Optimization Framework

The overall relationship among the key variables can be interpreted as follows. The anticline structure controls seam geometry. Seam geometry controls coal depth and overburden distribution. Overburden distribution controls the stripping ratio. Stripping ratio controls economic feasibility through BESR. Slope stability controls

the allowable pit wall geometry. Mining constraints control the spatial and vertical limits of the pit. Reserve estimation quantifies the final coal that can be mined after all geological, economic, geotechnical, and operational constraints are applied.

Table 7 confirms that the optimum Life of Mine pit design cannot be determined by a single variable. Pit shell 4 was selected not because it

produced the largest coal tonnage, but because it provided the best balance between mineable coal, waste volume, incremental stripping ratio, and BESR. Pit shell 5 produced more coal, but the additional waste requirement caused the incremental stripping ratio to exceed the economic limit. This means that maximizing coal tonnage without considering incremental waste removal may lead to an uneconomic pit expansion.

Table 7. Relationship and influence among key variables in Life of Mine Pit Optimization

Variable	Direct Influence	Effect on Pit Optimization
Anticline structure	Controls seam dip, seam elevation, and seam continuity	Determines coal geometry and overburden distribution
Seam geometry	Controls coal depth and accessibility	Influences pit shape and coal recovery
Waste volume	Represents overburden removal requirement	Determines stripping burden and mining cost
Mineable coal	Represents recoverable coal benefit	Determines revenue potential and reserve outcome
Incremental SR	Measures additional waste per additional coal	Determines marginal economic feasibility
BESR	Defines maximum economic stripping limit	Controls optimum pit shell selection
Slope stability	Controls safe pit wall configuration	Modifies economic pit shell into safe ultimate pit design
Mining constraints	Limit horizontal and vertical pit expansion	Restrict final pit boundary

Source: Authors' processing of research data (2026)

From a geotechnical perspective, the final design must also consider slope stability. The need to reduce sidewall slope angle from 35° to 31° and lowwall angle to approximately 12° under saturated conditions shows that the selected economic shell must be modified before becoming an applicable pit design. This relationship demonstrates that BESR defines the economic boundary, while slope stability defines the safe engineering boundary. The final ultimate pit design is therefore located at the intersection between economic feasibility and geotechnical acceptability.

The anticline structure influences the location and depth of coal seams. The BESR and incremental stripping ratio determine whether further pit expansion is economically justified. Slope stability determines whether the selected shell can be safely mined. Mining constraints define the practical boundary of the design. Reserve estimation then provides the final measurable output of the optimization process. In this study, the integrated evaluation resulted in the selection of pit

shell 4 as the optimum basis for the ultimate Life of Mine pit design, with a final coal reserve of 16,12 million tons.

Overall, the results support the argument that Life of Mine pit optimization in an anticline coal deposit must be interpreted as an integrated engineering decision. Geological structure controls seam geometry, seam geometry controls overburden distribution, overburden distribution controls stripping ratio, stripping ratio controls economic feasibility, and slope stability controls the safe transformation of an economic shell into an applicable final pit design (Spearing et al., 2022). The optimum pit shell is therefore not the shell with the maximum coal tonnage, but the shell that provides the best balance between additional coal recovery, additional waste removal, economic limit, slope stability, and operational constraints (Deutsch, 2023). This integrated interpretation is consistent with recent open-pit coal mining studies, which emphasize that mining boundary optimization must consider the coordination between geological

condition, mining sequence, stripping volume, and operational feasibility (Wen et al., 2026).

CONCLUSION

This study demonstrates that Life of Mine pit design optimization in an anticline coal deposit requires the integration of geological structure, Break-even Stripping Ratio, incremental stripping ratio, slope stability, mining constraints, and reserve estimation. The anticline structure controls seam geometry, seam elevation, and overburden distribution, which subsequently influence stripping ratio and pit shell development. Based on the available pit shell evaluation, pit shell 4 was selected as the optimum shell because its incremental stripping ratio of 5,04 remained below the BESR threshold of 5,8 bcm/ton, while the next shell exceeded the economic limit.

The slope stability evaluation shows that the selected economic pit shell cannot be directly converted into the final ultimate pit design without geotechnical adjustment. The highwall sectors were generally acceptable, while several sidewall and lowwall sections required flattening to satisfy slope stability requirements. The sidewall angle was reduced from 35° to 31°, while the lowwall required a gentler overall slope angle of approximately 12° under saturated conditions. These findings confirm that BESR defines the economic boundary of pit expansion, whereas slope stability defines the safe engineering boundary of the final pit design.

The optimized Life of Mine pit design resulted in a total coal reserve of 16,12 million tons, dominated by Seam A with 12,63 million tons. This confirms that the geometry and continuity of the dominant seam strongly control the final pit design and reserve outcome. Overall, the study indicates that the optimum pit shell is not necessarily the shell with the largest coal tonnage, but the shell that provides the best balance between additional coal recovery, waste removal, economic feasibility, slope stability, and operational constraints.

CONFLICTS OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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