Strategic mine method transformation to enhance marginal gold deposits and extend mine life

Hidayatullah Sidiq[1*], *Shofa* Rijalul Haq[2], *Aldin* Ardian[2], *Lidana* Erfiandri[3]

[1]Mining Engineering Department, Institut Teknologi Nasional Yogyakarta, Yogyakarta, Indonesia
[2]Mining Engineering Department, Universitas Pembangunan Nasional "Veteran" Yogyakarta, Yogyakarta, Indonesia
[3]PT Studio Mineral Batubara, Yogyakarta, Indonesia

Abstract. The economic viability of marginal gold reserves remains a major challenge in the final stages of mining operations, particularly when constrained by underground mining methods. This study investigates a strategic transition from underground to open-pit mining to enhance the economic potential of marginal gold deposits and extend the overall life of mine. Focusing on a gold mine approaching depletion, the research evaluates the technical, economic, and operational implications of converting the mining method to access previously uneconomic ore zones. A comparative analysis was carried out between underground and open-pit scenarios using parameters such as stripping ratio, recovery factor, cut-off grade, and Net Present Value (NPV). A sensitivity analysis was also conducted to assess the influence of gold price, mining cost, and ore grade on project feasibility and risk. The results demonstrate that transitioning to open-pit mining significantly increases recoverable reserves by reclassifying marginal zones as economically viable, leading to improved project NPV and extended life of mine. In addition to economic benefits, the transformation supports operational continuity and improved resource utilization. Nevertheless, geotechnical stability, environmental management, and regulatory compliance remain critical aspects to be addressed in implementing such a transition.

1 Introduction

Most gold mines are entering their final phase, with remaining reserves of marginal grade scattered around old openings (remnant stopes, crown pillars, and pillars) or at low grades that were previously uneconomic. To extend mine life and convert marginal resources into economic reserves, companies are increasingly relying on mining method transformation, strategically integrating or shifting from open-pit to underground mining. Recent research has characterized this transformation as a cross-method strategic

* Corresponding author: hidayatullah@itny.ac.id

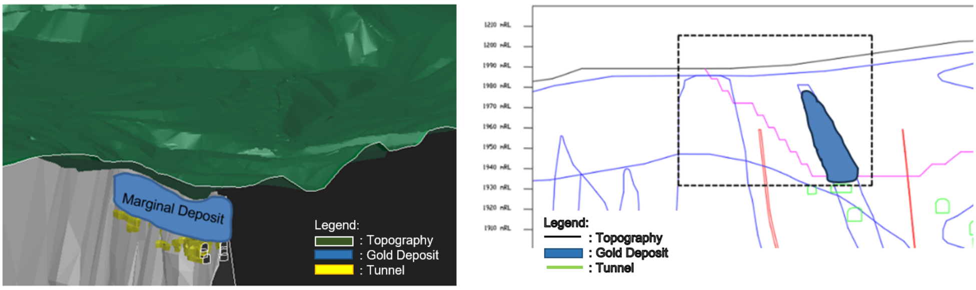
optimization problem that must balance net present value (NPV), geotechnical risk (crown pillar/void stability), price uncertainty, and mining sequencing [1].

From a mine planning perspective, recent literature has developed simultaneous OP-UG optimization models to determine optimal transition points/depths, integrated production schedules, and void-constrained pit boundaries. These approaches-ranging from graph-closure/LP-MIP formulations to stochastic schemes-demonstrate that method transformation decisions can improve NPV while simultaneously capturing marginal reserves previously trapped by single-method constraints [2-3]. Geotechnically, crown pillar stability and interactions with existing slopes are key limiting factors when implementing transformation methods. Previous research has shown that crown pillar geometry (thickness, span, slope) and slope geometry influence stress response and failure mechanisms; engineering solutions such as artificial crown pillars/pastefills can be used to maintain safety and enable extraction of values from marginal zones. Recent numerical/experimental findings emphasize the importance of void mapping, local slope design in overmined areas, and controlled blasting strategies [4-5].

Thus, most current mining methods transition from open-pit to underground or a combination of both. No research has optimized marginal reserves from underground to open-pit mining. Therefore, this study aims to optimize marginal reserves, thereby extending the mine life by one year beyond the normal reserve life. This research is significant because it provides new insights into the rare phenomenon of transitioning from underground mining to open-pit mining to extract marginal gold reserves. The study contributes to the scientific understanding of mining method transitions, offers practical guidance for optimizing the recovery of near surface marginal deposits, and supports strategic decision making in mine planning especially in contexts where such transitions are uncommon globally.

2 Orebody condition

In the initial condition of the marginal gold model, underground mining has already been conducted in the lower section. However, as the global gold price increases and operational cost efficiency improves, the upper part of the deposit, previously considered uneconomic for underground extraction, becomes viable for open-pit mining. This transition enables the recovery of additional resources that were previously left as crown pillars or safety buffers above underground stopes. By converting the upper portion of the deposit into an open-pit operation, the overall resource utilization and mine life can be extended while reducing the cost per tonne of ore extracted. Furthermore, this integrated approach facilitates improved access, simplified haulage, and a more continuous production schedule, ultimately optimizing the economic potential of the remaining reserves.



(a) (b)

Fig. 1. (a) 3d model marginal deposit, (b) section 2d marginal deposit

Fig. 1a illustrates the three-dimensional representation of the marginal deposit targeted for optimization, whereas Fig. 1b presents its two-dimensional geological configuration. Fig. 1 shows the whole picture; the area between the existing underground tunnels and the current surface topography represents the gold ore zone to be optimized. This intermediate zone often contains economically significant ore that was previously excluded from underground operations due to geotechnical or economic constraints. Through the application of open-pit mining methods, this zone can now be exploited efficiently by removing the overlying waste material and accessing the remaining ore blocks directly from the surface.

3 Consideration of technical and economic factors

Gold is a strategic mining commodity that plays a vital role in the global economy, serving as both an investment instrument and an indicator of financial market instability. Fundamental factors, including inflation, monetary policy, exchange rates, and international geopolitical conditions, influence the dynamics of the gold price. For the mining industry, changes in gold prices have direct consequences for reserve feasibility evaluations, production strategies, and investment decisions. Price increases can make marginal reserves more economical, while price decreases can limit mining activity. Therefore, historical gold price analysis is necessary to understand market trends that influence strategic mining decisions. Fig. 2 below presents global gold price movements from early 2020 to mid-2024 based on the Mineral Price benchmarks (HMA) in Indonesia and the London Bullion Market Association (LBMA) indices.

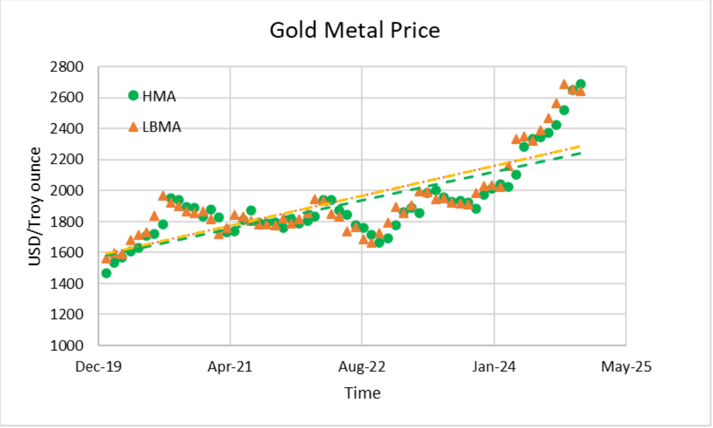


Fig. 2. Historical gold price 2020-2024

Fig. 2 shows the historical trend of gold prices from early 2020 to mid-2024, exhibiting a fluctuation pattern closely tied to global macroeconomic dynamics, financial market volatility, and geopolitical uncertainty. The two benchmark indices, the HMA (green circle) and the LBMA (orange triangle), demonstrate consistent and mutually reinforcing price movements, illustrating the direction of the global gold market. In early 2020, gold prices hovered around USD 1,400–1,600 per fine troy ounce (USD/oz), reflecting the stability of the commodity market before the onset of external shocks. A significant surge occurred in the first half of 2020, triggered by the COVID-19 pandemic, which caused global uncertainty and increased investor preference for safe-haven assets. This structural change pushed gold prices to nearly $ 2,000 per troy ounce by mid-2020, confirming gold's role as a hedge against systemic risk.

The 2021-2022 period was marked by a consolidation phase, with gold prices fluctuating in the range of USD 1,700-1,900 per troy ounce. This pattern reflects the interaction between global economic recovery, tighter monetary policy, and fluctuations in the U.S. dollar exchange rate. Despite relatively high price volatility, the medium-term trend still indicates potential for upside, in line with fundamental demand factors from the industrial and jewelry sectors, as well as investment activity.

In late 2022 and early 2024, gold prices resumed a bullish rally, driven by sustained global inflationary pressures, central bank gold accumulation, and rising geopolitical risks in strategic global regions. In early 2024, gold prices reached a high of USD 2,600 per troy ounce, marking one of the highest levels in the past decade. Trend regression analysis (dotted line) shows a significant long-term upward trend, confirming gold's position as a strategic commodity in global investment portfolios.

3.1 Technical factors

These geotechnical characteristics directly influence slope stability, as zones with stronger, more massive rocks can sustain steeper slope angles. At the same time, areas composed of weaker, fractured materials require flatter designs to maintain overall stability. Therefore, the excavation and slope design should integrate rock mass

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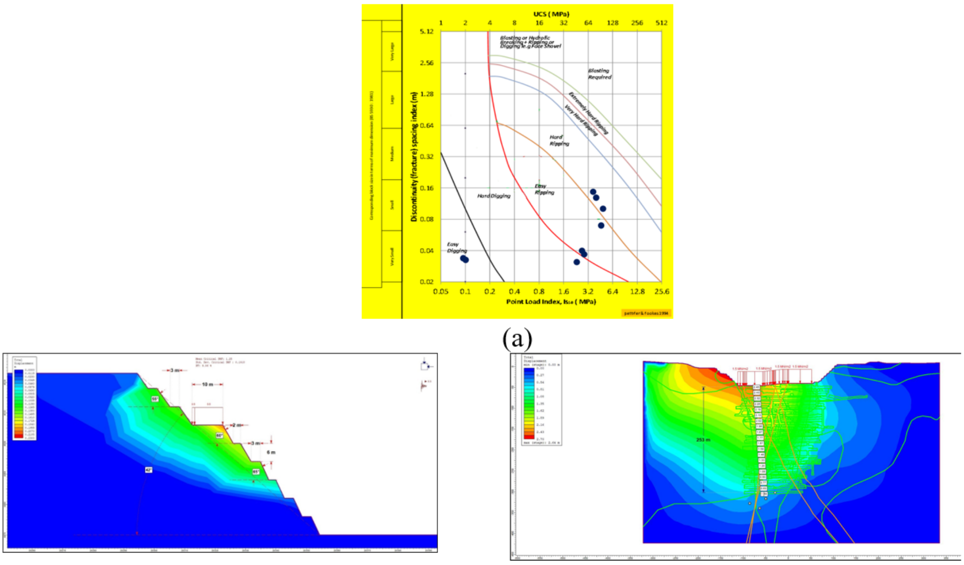
properties with field observations to ensure safe and cost-effective surface mining operations, minimizing the risk of failure in both pit walls and near-surface openings.



(a)

(b)

(c)

Fig. 3. (a) Redrawn the excavatability assessment chart based on Pettifer & Fookes [6], (b) Open pit slope stability analysis geometry recommendations, (c) Results of modeling mining front conditions against underground openings.

Based on geotechnical data obtained from both laboratory and field tests, the excavation is recommended to range from easy digging to hard ripping conditions. The classification shown in Fig. 3 a. indicates that the rock mass, represented by andesite, breccia, porphyritic materials, and vein materials, varies in strength and discontinuity spacing, resulting in different excavation responses. Andesite and breccia plot within the hard ripping zone, implying that mechanical ripping using dozers or hydraulic breakers will be required for efficient excavation. In contrast, vein and porphyritic rocks fall into the easy to moderate digging range, where conventional excavators or backhoes are sufficient.

The slope stability analysis, as illustrated in Fig. 3b, demonstrates that the designed overall slope geometry, with bench face angles ranging from 55° to 65°, inter-ramp bench widths of 2-3 m, and berm spacing of 6-10 m, achieves a mean critical Factor of Safety (FoS) of 1.25, indicating a stable configuration under static conditions. The total displacement contour shows maximum deformation values below 0.23 m, concentrated near the toe area, suggesting localized plastic deformation but no indication of global failure. The critical slip surface intersects mainly through the weaker, more fractured zones identified in the rock mass classification (breccia and vein materials), which correspond to easy digging and hard ripping conditions.

The numerical modeling presented in Fig. 3c, illustrates the total displacement distribution along the vertical section encompassing both the existing underground workings and the proposed surface excavation zone. The underground infrastructure extends approximately 253 m below the surface, consisting of a complex network of drifts, ramps, and stopes. The applied surface load of 1.5 MN/m² represents the expected stress concentration from the advancing open-pit operation above. The deformation contours indicate maximum total displacements of up to 2.64 m, localized near the upper part of the underground void system directly beneath the planned pit floor. These high-strain zones correspond to stress redistribution resulting from the removal of the overburden and the subsequent loss of confinement pressure.

3.2 Economic factors

Looking at the positive trend in global gold prices, sourced from the LBMA and Minerba websites, gold prices have shown an annual increase of 5.22%. For the mining sector, this gold price dynamic has crucial technical implications, particularly in production planning, mine feasibility evaluation, and cut-off grade (CoG) determination. The price surge increases the economic potential of previously unminable marginal reserves and opens up opportunities for implementing layered mining strategies. Initially, underground mining is carried out, followed by open-pit mining to optimize gold ore resources above the crown pillar. Figure 4 shows the correlation of gold price and cut-off grade (CoG).

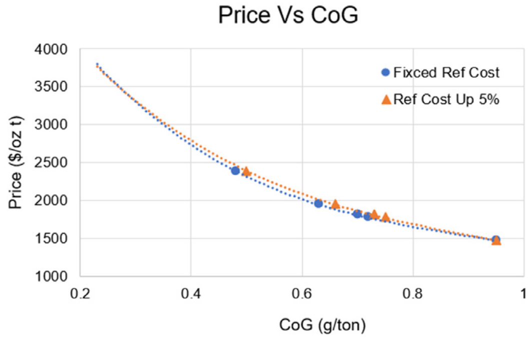


Fig. 4. Correlation of gold price and cut-off grade (CoG).

The figure above illustrates the relationship between the gold price (USD/oz) and cut-off grade (CoG, g/t) under two different scenarios, considering changes in ore processing costs. The blue line represents the base case, where processing costs are held constant. The orange line represents a scenario in which processing costs increase by 5% from their initial level. Both curves demonstrate a negative, non-linear relationship between gold price and CoG. The higher the gold price, the lower the CoG that remains economically viable to mine. This pattern illustrates the elasticity of mining economics to metal prices, any increase in the gold price directly lowers the economic grade (CoG), thereby expanding the volume of economically mineable reserves. A 5% increase in processing costs has only a moderate effect on CoG, but significantly impacts profit margins per ounce of gold. In the long run, this cost factor will determine whether a mining operation can sustainably extract marginal ore.

4 Results and discussion

Based on the technical and economic evaluations conducted, an optimal pit design has been developed. The final configuration represents the most feasible balance between maximizing ore recovery and ensuring geotechnical stability under the given site conditions. This optimization process integrates geological modeling, slope design parameters, and economic analysis, including Net Present Value (NPV) sensitivity to variations in price and operational costs [7]. The resulting pit layout provides a stable and economically viable configuration for transitioning from underground to surface mining operations.

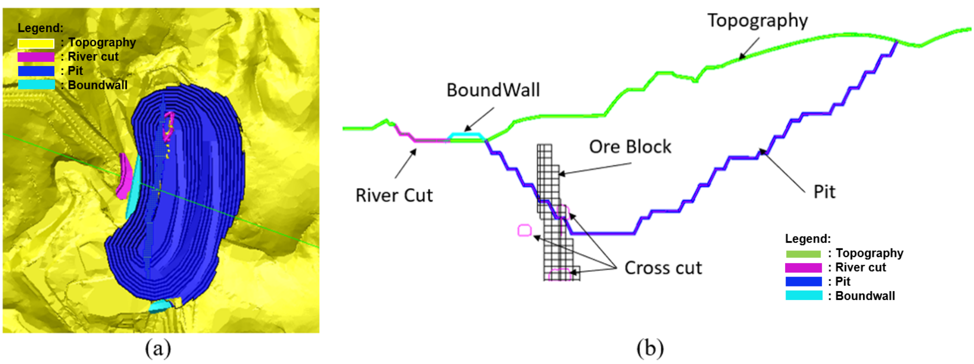


Fig. 5. Design pit optimization, (a) 3D top view design, (b) 2D cross-section.

Fig. 5 above shows that the optimal pit design for the mine operating period is 10 months. With the addition of ore that can be extracted through open-pit mining, this transition in mining method has the potential to extend the life of the mine. Optimization of pit design resulted in the production of 175 thousand tons of ore and can be extracted into 500 kg of Au, with waste being 1.3 million cubic meters.

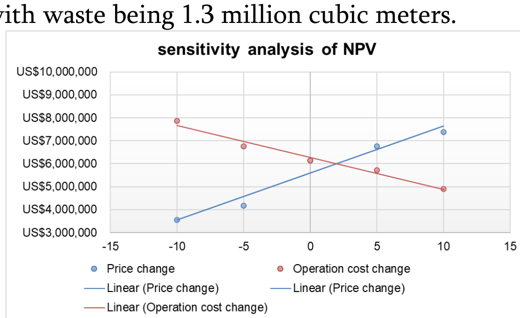


Fig. 6. Sensitivity graph of NPV analysis of price changes and operational costs.

Fig. 6 shows that the maximum NPV obtained from open-pit mining of both pits is USD 6.1 million, with an IRR of 64.1%. Price change was found to be the most sensitive parameter compared to cost change, where a 5% decrease in gold price caused a downward trend in the NPV curve of the sensitivity analysis.

5 Conclusion

The increase in global gold prices has significantly influenced the cut-off grade (CoG) applied in mining operations. As a result, previously uneconomic marginal gold deposits have become economically feasible and can now be exploited using open-pit mining methods. The transition from underground to open-pit mining not only improves resource recovery but also enhances project profitability, yielding a maximum NPV of USD 6.1 million and an IRR of 64.1%. Moreover, this transition contributes to an extension of the overall mine life by approximately 10 months, demonstrating that strategic economic and technical re-evaluation can unlock additional value from marginal ore zones while maintaining operational sustainability.

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