Bench height effects on economical parameters at open pit mine

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ABSTRACT

The selection of optimal bench height is crucial to the design of open-pit mines. The bench height influences selectivity, dilution, blast design, and equipment selection, which in turn impacts capital and operating costs and the size and value of the final pit. This study investigates the effects of different bench heights (10, 15, and 20 m) on the grades, unit operations, costs, design, and economic value of final pits for different production rates. We used vein and massive deposit types as case studies to gain a comprehensive insight. The results indicate that increasing the bench height for vein deposits leads to an increase in the stripping ratio and reduction in average grade due to low selectivity and high dilution. Conversely, massive deposits exhibit less sensitivity to bench height variations. In both deposit types, larger bench heights are associated with increased blast pattern size and equipment dimensions, which can lead to lower operating costs, with drilling being the unit operation most positively impacted. Blasting costs, on the other hand, experience the least reduction. Regarding production planning, our findings reveal that for vein deposits, the higher capital cost of equipment and the negative impact of dilution from using larger bench heights far outweigh the benefits of lower operating costs. In contrast, for massive deposits, selecting larger bench heights and high-capacity equipment can still be advantageous due to lower operating costs and increased project value at high production rates.

Keywords: Bench height, equipment selection, production rate, unit operation, Mining cost, open pit min

1. INTRODUCTION

One of the main tasks in the strategic planning of an open-pit mine is the operational design of the final pit, which aims to maximize the return on investment (Alegre et al., 2019). The ultimate final pit limit will define the amount of extractable mineral, metal content, and the associated amount of waste to be moved during the life of the mine (Armstrong, 1990). It will also impose restrictions on the location of peripheral infrastructure for the operation, such as roads, waste dumps, processing plant, buildings, etc. Some key elements that affect the design of the final pit are: geology of the deposit, grade distribution, location of mineralization, allowable slopes, production rates, bench height, mining costs, processing costs, metallurgical recovery, and market considerations (Armstrong, 1990). Considering these factors, it is understood that most of them are not under the control of mining engineers. However, production strategies, design criteria such as bench height, and equipment selection are determined by mining engineers.

The determination of bench height is a fundamental and challenging issue for most open pit mines. Although an optimal decision is desired, there is no standardized approach for its selection because it is a function of multiple factors. The bench height depends on the physical characteristics of the deposit, the level of selectivity required to separate ore from waste with loading equipment, production rate, size, and type of equipment selected (Rossi Mario E.and Deutsch, 2014). In addition to being conditioned by many factors, bench height also impacts multiple aspects that could affect the economics of an open pit mining project.

In order to carry out mine planning and design, a block model of the deposit is required. In open-pit mines, it is common to match the block height in the block model with the determined bench height, which immediately impacts the selectivity and dilution of the operation (Ebrahimi, 2013). An increase in bench height results in increased dilution (A. Bozorgebrahimi, Hall, et al., 2005), whereas smaller bench heights allow for more selective extraction. The decision to select a bench height that minimizes dilution is influenced by the size of the equipment, market conditions, and inherent characteristics of the mineral resource, such as grade distribution, ore strength, and the overall shape of the deposit (Hustrulid et al., 2013).

In drill and blast operations, the bench height influences the blast hole diameter, which is a fundamental parameter in blast pattern design and the selection of drilling equipment (Bhandari, 1997; Gokhale, 2010; Kose et al., 2005; Lopez, 1995). The cutting height and bucket capacity are also a function of the bench height in the material loading operation. Therefore, the selected bench height depends on the loading equipment (Hekmat et al., 2011; Swanepoel, 2005). The capacity of the loading equipment determines the size of the truck used to haul the material. The goal is to maximize the utilization of the equipment by matching the haulage equipment to the loading equipment. For an efficient system, the number of passes required to fill a haulage truck is between 3 to 5 (Bozorgebrahimi, Hall, & Morin, 2005).

This paper explores the impact of bench height on the tonnage and grade of ore material in vein and massive copper deposits, considering bench heights of 10, 15, and 20 meters. Additionally, it establishes relationships between bench height and the size of drilling, loading, and haulage equipment and estimates operational costs based on the size of the main equipment. The economic value of the final pit is evaluated for each scenario, and the differences in value resulting from the bench height for different production rates are quantified. This comprehensive approach provides insights into the optimal bench height selection for open pit mines by considering the combined effect of geological, geometrical, and economic factors of the mine.

2. RELEVANT LITERATURE

Several studies have been conducted to investigate the significance of bench height in open-pit mining projects. Glacken et al. (2000) assessed the impact of different bench heights and block dimensions on resource estimation through conditional simulation. Swanepoel (2005) investigated how bench height and equipment selection impact the efficient use of mineral resources. The author evaluated the impact of selectivity during loading operations by conducting 3D simulation across a range of bench heights on the resource utilization and net present value of an Iron ore deposit. Kose et al. (2005) analyzed the most economic bench height in a quarry mine with ramp slopes of 8% and 10% (Kose et al., 2005). Their study obtained useful relationships to determine unit operation costs based on the bench height and drilling diameter. The impact of block dimensions on the design and planning of an open pit mine was evaluated by Jara et al. (2006) for three cases. In their research, the impact on selectivity, dilution, metal content, and net present value (NPV) was demonstrated, but no consideration was given to the effect of block size on operational and capital costs. Soltanmohammadi et al. (2010) proposed a methodology to select bench height through different alternatives using the VIKOR analytical method. Using the multiple criteria optimization method, the authors introduced an approach in which the advantages and disadvantages of using various bench heights in an open pit mine were combined to obtain the practical bench height for a case study. Hekmat & Osanloo (2017) determined the capital and operating costs of open pit mining by correlating blast-hole diameter and bucket capacity with bench (block) height. The study showed that block height has a greater influence on mining costs than horizontal block dimensions.

While some understanding exists regarding the individual factors that may influence or be influenced by bench height, there is a dearth of research that comprehensively considers the combined effects of geological, geometrical, and economic factors on bench height. This study aims to determine the optimal bench height for open pit mines by conducting a comparative analysis of various scenarios. The impact of bench height on the design and economic value of the final pit is evaluated for two types of vein and massive deposits.

3. CASE STUDY

This study analyzes the effect of bench heights on different deposit shapes. Figure 1 shows the isometric view (a) and north-south section (b) of the vein and massive copper deposits. The grade distribution reveals that the vein deposit contains higher copper grades. Table 1 presents the characteristics of the deposits.

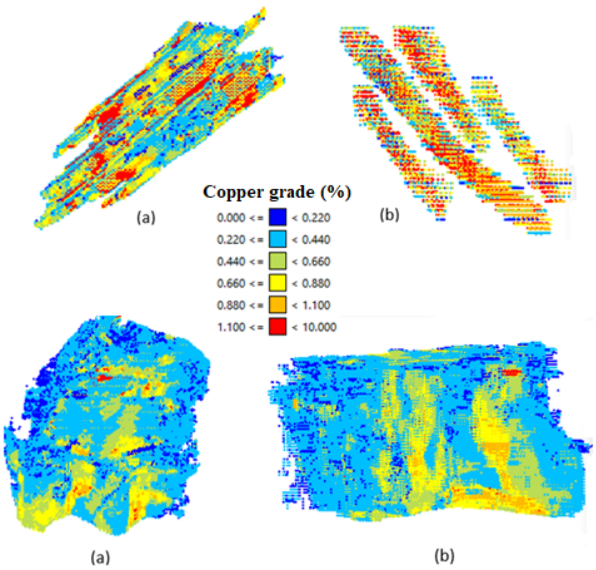

Figure 1 Shape and Grade Distribution of Vein deposit (top) and Massive Deposits (bottom) from an Isometric View (a) and North-South Section (b).

This study involved three different block models, with dimensions of 10 × 10 × 10, 10 × 10 × 15, and 10 × 10 × 20 cubic meters. Figure 2 shows the grade-tonnage curve for various bench heights. An increase in the bench height for the massive deposit had no effect on the tonnage or average grade of the deposit (Figure 2). However, for the vein deposit, increasing the bench height from 10 to 15 meters resulted in an 8% increase in tonnage and a 20% decrease in average grade at a cutoff grade of 0.2%. When the cutoff grade was increased to more than 0.5%, the tonnage of material for greater bench heights decreased, demonstrating the dilution effect on reducing the tonnage and average grade of the high-grade portion of the deposit. Furthermore, comparing the grade-tonnage curves for both deposits shows that bench height can highly affect the dilution of the vein deposit. As a result, it is necessary to select the optimal bench height in order to minimize dilution and maximize recovery, particularly for high-grade vein deposits.

Another observation that can be made from Figure 2 is that the size of the massive deposit is roughly six times larger than the vein deposit. As a result, selectivity in the massive deposit is easier even with more tonnage to extract at lower cut-off grades.

4. BENCH HEIGHT AND MINING COST

Cost estimation in mining is a complex task due to the unique characteristics of each operation. As Stenbbins & Leinart (2011) mentioned: “There are probably as many ways to estimate mining costs as there are cost estimators”. During the prefeasibility stage, cost evaluatio can be derived from similar operations. However, it is important to consider the fact that accounting practices may vary in each mining project. A reliable cost estimation methodology involves combining historical data with practical and engineering judgments (Zimmer, 1996). O’Hara & Suboleski (1992) proposed a parametric model for estimating costs in open pit and underground mines based on daily production rate. Hekmat & Osanloo (2017) applied this method to calculate mining costs based on block size in an open pit mine.

Table 1 Deposits characterization

Characteristic	Vein deposit	Massive deposit
Thickness (m)	50 - 100	More than 100
Inclination (degrees)	50	Vertical
Grade distribution	Erratic	Gradational
Model dimensional (m)	490 ×1040 × 450	1200 × 1140 × 640
Cutoff grade (%)	0.2	0.2
Maximum grade (%)	4.29	3.08
Average grade (%)	0.91	0.41
Block size (m)	10 × 10 × 10	10 × 10 × 10

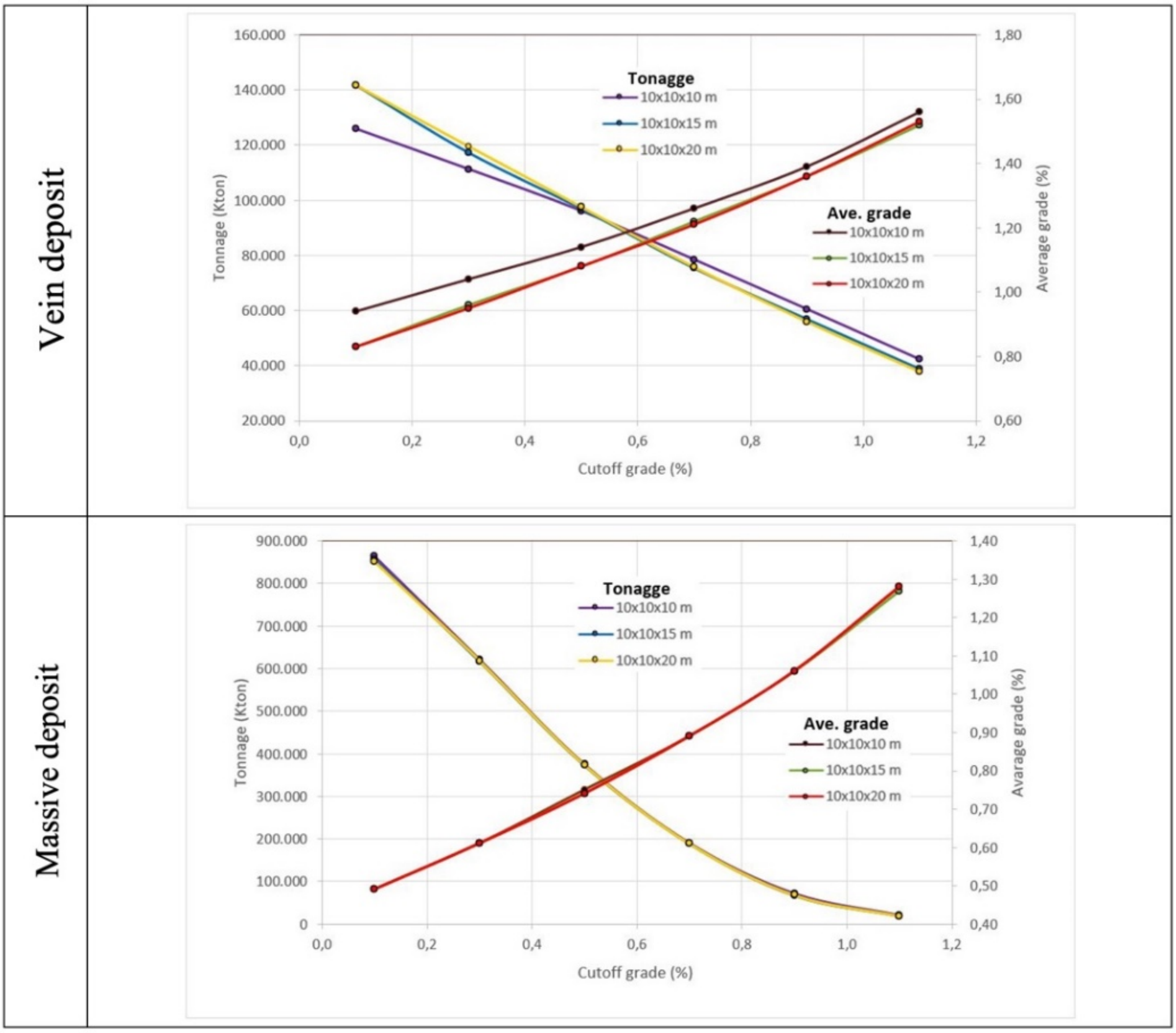

Figure 2 Grade-tonnage curve for different bench heights in two types of deposits under study.

Currently, most evaluators prefer a more detailed and engineering-based approach for cost estimation (Stenbbins & Leinart, 2011). This process entails designing the ultimate pit, determining pushbacks, calculating equipment requirements, estimating the necessary supplies and labor, and assessing the cost for each component.

In this study, the capital and operating costs of mining were calculated based on the unit operations at the mine and the equipment involved in these activities, whether related to their purchase or operation. Additionally, administration costs were considered at 15% of the operating cost when calculating the discounted cash flow for different scenarios. Therefore, the first step in cost estimation was equipment selection for each scenario of bench height, with the objective of meeting the required production rate while minimizing costs. Several researchers have used various techniques in equipment selection (Berkhimer, 2011; Burt & Caccetta, 2018). These studies mentioned classical techniques involving deterministic formulas (Vujic et al., 2011), linear and integer programming (Moradi-Afrapoli et al., 2021), simulation (Upadhyay, Tabesh, et al., 2021), queueing theory, expert systems, and artificial intelligence (Nobahar et al., 2022). In this study, a deterministic process incorporating bench height was utilized as the primary selection criterion.

4.1 Loading equipment selection

The process of selecting equipment based on bench height began with choosing the appropriate loading equipment since the bench height has a direct impact on the maximum cutting height of the loading equipment. Figure 3 illustrates the relationship between the cutting height and bucket capacity of hydraulic shovels. This graph was created by compiling the optimal working ranges of all available shovels on the market. The best trend line of the points reveals the relation between bench height (h) in meters and bucket capacity (BC) in cubic meters as given in equation 1.

$$BC = 0.0113h^{2.76} \quad (1)$$

4.2 Haulage equipment selection

Given the bucket capacity of the shovel, the truck capacity was defined by considering the rule that each truck should be loaded by three to six cycles of the shovel. In this study, it was assumed that each truck is loaded by 4 cycles of the shovel, provided that such a truck capacity exists on the market. In case it doesn't, 5 or 6 cycles were considered instead. Therefore, with knowledge of the rock density (ρ) and bucket fill factor (F_f) of the shovel, the truck capacity (T_C) is calculated in equation 2.

$$T_C = Q * \rho * F_f * n \quad (2)$$

In equation 2, Q represents the bucket capacity of the shovel, and n is the number of cycles of the shovel to fill a truck.

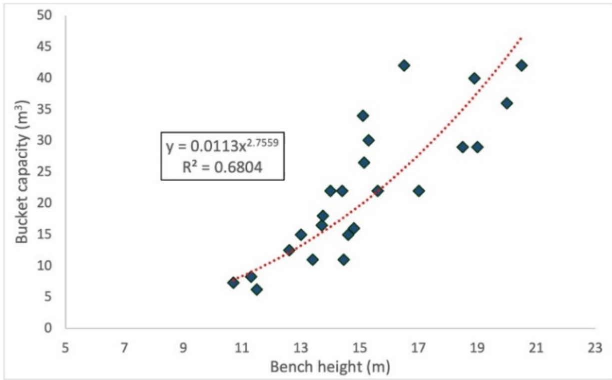

Figure 3 Relation between the shovel capacity and bench height.

4.3 Drill and blasting

The bench height in an open pit mine plays a crucial role in determining the selection of drillhole equipment. This equipment must be capable of drilling holes that match the height of the benches, along with an additional 1 to 3 meters of subdrilling. As the bench height increases, the selection of larger drilling equipment becomes necessary, leading to higher capital costs. The diameter of the drillholes is directly influenced by the bench height (Ayala-Carcedo, 2017). Consequently, increasing the bench height results in blast holes with a greater diameter.

According to Ash Equipments, there is a direct relationship between hole diameter and burden, leading to an increase in the distance between burden and spacing as the bench height rises. Such drillhole patterns often result in oversize bulders and toes after the explosion (Leng et al., 2020). However, it is important to consider the impact of the rock type on fragmentation and make appropriate decisions regarding hole positioning and rock characteristics to achieve the desired fragmentation. Additionally, larger rock distribution necessitates the use of larger loading and haulage equipment.

Many studies and empirical equations have been used to establish the relationship between the bench height and blasthole diameter (Adhikari, 1999; Mostafa et al., 2020). Figure 4 shows the correlation between the borehole diameter and the bucket capacity of loading equipment, compiled using published data (Gokhale, 2010).

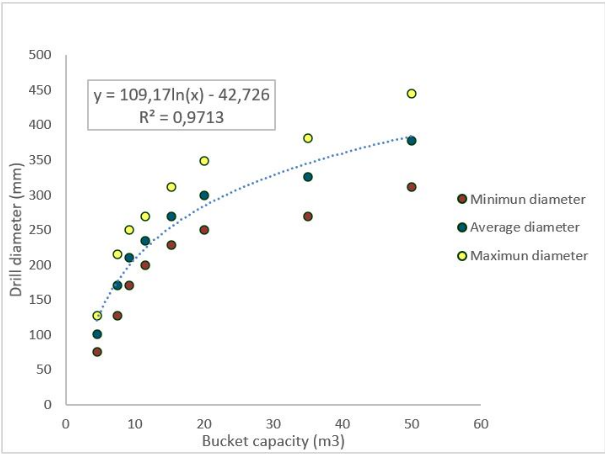

Figure 4 Relation between the shovel capacity and blasthole diameter.

Finally, given the drill diameter, the blashole pattern for each bench height was designed using the Ash method (Ayala-Carcedo, 2017). The calculations were based on medium rock quality and low-density explosive material (ANFO). The equipment size and blasting pattern for each bench height are summarized in Table 2.

4.4 Operational cost of unit operations

This research assumes that the total operating costs of the mine are the sum of the operational costs for drilling, blasting, loading, and hauling. The cost data comes from InfoMine (2013), an industry standard for cost estimation, and contains the capital and operating costs for over 3,000 equipment items commonly used in mines and mills worldwide. The operational costs in US$/h are published annually by InfoMine and include maintenance costs, fuel, electricity, lubricants, tires, and wear parts, to which the operators' salary is added. Using the information obtained in Table 2, the total cost is divided by the production rates of each type and size of equipment in tons/h. As a result, the cost per unit of material extracted in US$/ton was calculated.

Table 2 The blast design parameters for each bench height

Parameter	Bench height		
	10	15	20
Drill diameter (mm)	174	295	365
Burden (m)	4.4	7.4	9.1
Spacing (m)	6.5	11.1	13.7
Stemming (m)	4.4	7.4	9.1
Subdrilling (m)	1.3	2.2	2.7
Rock volume per hole (m^3)	286	1232.1	2493.4
Shovel capacity (m^3)	7.3	22	42
Truck capacity (ton)	62	188	359

4.4.1 Drilling operation

The operating costs of track-mounted rotary drills for different borehole diameters are presented in Figure 5. It can be observed that increasing the borehole diameter results in higher operating costs for the drills. Since larger equipment involves a more complex system with higher energy consumption and greater maintenance requirements, the operational costs increase accordingly. On the other hand, the operating costs per unit of material decrease as the drill diameter increases, due to higher productivity (Figure 6). Increasing the borehole diameter makes it possible to increase the borehole spacing, meaning that fewer holes are needed to fragment the same volume of rock. Equation 3 demonstrates the operational cost of drilling (C_d) in dollars per ton, based on the drill diameter (∅), in millimeters.

$$C_d = 320.117 * \emptyset^{-1.437} \quad (3)$$

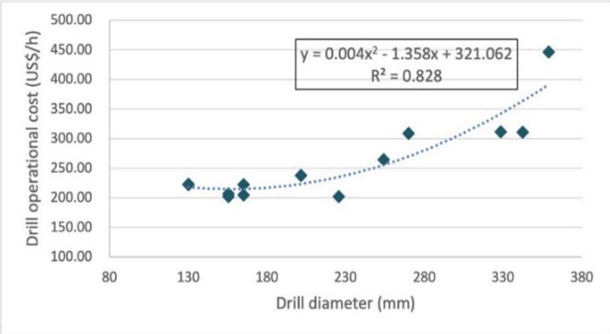

Figure 5 Hourly Operational cost of track-mounted rotary drill for different borehole diameters.

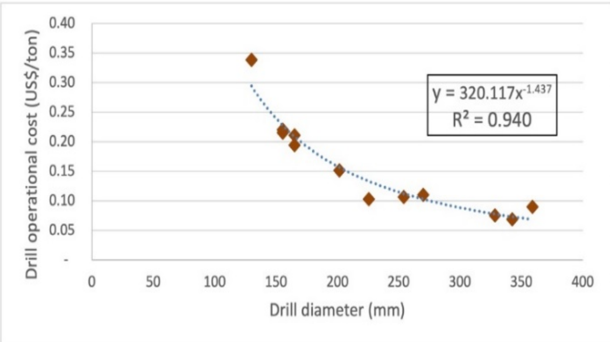

Figure 6 The relation between drilling cost per ton and borehole diameter.

4.4.2 Blasting Operation

The first step in estimating the blasting costs was to calculate the number of boreholes needed to fragment a certain tonnage of material (100kton). Then, the amount of explosive material required in each hole (γ) was calculated using equation 4 (Firth & Mousset-Jones, 2003).

$$\gamma = \left(\frac{\pi * \emptyset^2}{4}\right) * (L - T) * \rho_e \quad (4)$$

In equation 4, $\emptyset$ (m) is the borehole diameter, L (m) represents the total height of the borehole, T (m) is stemming and ρ_e (kg/m^3) represents the density of explosive material.

In addition to calculating the weight of explosive material, the number of primers was also determined, with one primer considered for each borehole. The amount of detonation cord was estimated by multiplying the total length of drilling by 1.3. Finally, labor costs and overhead expenses were assumed to be 10% of the total material cost.

Table 3 summarizes the calculations for the required explosive material, estimated costs to fragment 100,000 tons of material, and the cost of blasting per ton of material. It can be seen in Table 3 that the number of boreholes and detonation cords decreases with an increase in bench height and hole diameter. By increasing the bench height up to 15 m, The required explosive material (ANFO) slightly decreases. However, by increasing the bench height to 20 meters, the required amount of ANFO increases due to the increase in the length and diameter of the boreholes. Therefore, there is a minimum blasting cost for a bench height of 15 meters, beyond which the total blasting cost increases. Figure 7 illustrates the changes in blasting cost based on borehole diameter, which is a function of the bench height.

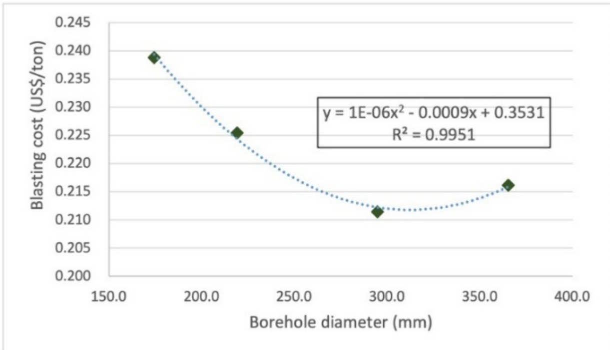

Figure 7 Blasting cost for different borehole diameter

4.4.3 Loading operation

The operating costs of hydraulic shovels with different bucket capacities were obtained using the equipment cost estimator (InfoMine, 2013). As shown in Figure 8, loading costs for hydraulic shovels decrease as the capacity increases due to the higher productivity of larger shovels. Equation 5 calculates the operational loading cost (C_L) in dollars per ton, based on the bench height (h) in Equation 1 and the trend line from Figure 8.

$$C_L = 1.3h^{-0.5} \quad (5)$$

Table 3 Required explosive material and blasting costs for different bench heights

Parameter	Bench height (m)			
	10	12	15	20
Borehole diameter (mm)	174.3	219.1	294.7	365.3
Number of holes (Number/100Kt)	135	71	31	15
Detonation cord (M/100Kt)	1,983	1,262	704	454
Weight of ANFO (kg/100Kt)	17,886.3	17,514.2	16,885.9	17,509.1
Specific charge (kg/m^3)	0.47	0.46	0.44	0.46
ANFO cost (K$/100Kt)	19.7	19.3	18.6	19.3
Primer cost (K$/100Kt)	0.6	0.3	0.2	0.1
Cost of detonation cord (K$/100Kt)	1.4	0.9	0.5	0.3
Labor cost (K$/100Kt)	2.2	2	1.9	2
Total cost (K$/100Kt)	23.9	22.5	21.1	21.6
Total cost (US$/ton)	0.24	0.23	0.21	0.22

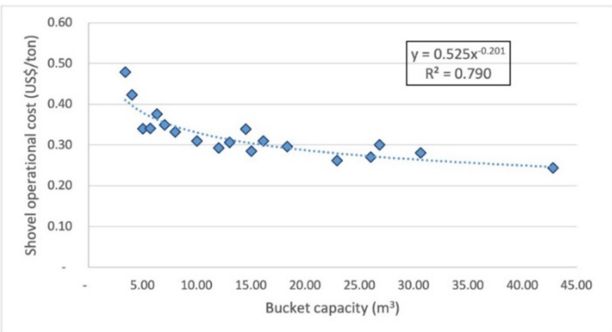

Figure 8 The relationship between loading costs and bucket capacity

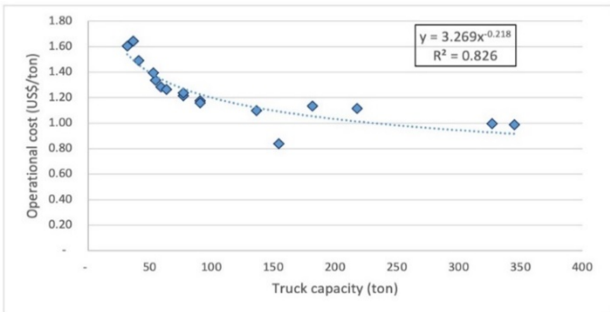

Figure 9 Haulage cost for different truck capacities

4.4.4 Haulage operation

The equipment cost estimator was used to determine the operational costs of trucks based on their capacity in US dollars per hour (InfoMine, 2013). The route profile must be defined to calculate truck performance. For this research, a single spiral road with an average of 3 km and a 10% slope was assumed for all bench scenarios. However, as the bench height changes, the road length changes.

Truck speed in various road sections and loading and dumping times were defined based on Caterpillar equipment data. Figure 9 shows a downward trend in costs per ton as truck capacity increases, indicating higher productivity. However, this trend is less pronounced than in the case of drills and shovels. This may be due to the significant impact of tire consumption and useful life on operational costs for truck transportation systems. Tire life is shorter for larger trucks due to higher air pressure and operating temperatures. The cost is adjusted according to the actual route profile provided by the operational design (including bench height) of each scenario.

Table 4 Pit optimization parameters for each bench height

Parameter	Bench height (m)		
	10	15	20
Mining cost (US$/ton)	2.11	1.63	1.44
Processing cost (US$/ton)	10	10	10
Refinery cost (US$/lb.)	0.4	0.4	0.4
Processing recovery (%)	90	90	90
Copper price (US$/lb.)	3	3	3
Cutoff grade (%)	0.235	0.225	0.222
Overall pit slope (degrees)	45	45	45
Bench angle (degrees)	70	70	70
Bench width (m)	6	9	12
Ramp grade (%)	10	10	10
Ramp width (m)	26	37	43

5. BENCH HEIGHT AND ULTIMATE PIT DESIGN

The economic block value and cutoff grade were calculated for varying bench heights for the two deposits. The inputs included the mining (total unit operations cost), processing, and refining costs for each scenario (table 4). The processing and refining cost did not change for different bench heights. The optimum pit was then determined based on the Learch & Grossman method in the Vulcan software using the economic block model and a revenue factor of 1. Table 5 shows the results of the optimum pits for each scenario. For both reserves, the amount of ore, waste, and metal content increases as the bench height increases. Due to ore dilution, the average grade in the vein-type deposit decreases more noticeably with increasing bench height compared to the massive deposit (Table 5).

The ultimate pit was designed by adding a spiral road and safety benches to each optimum pit and using the pit geometrical parameters in Table 4.

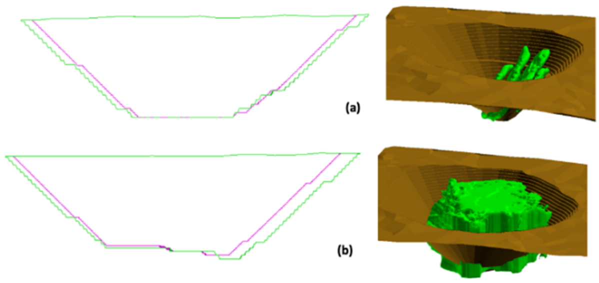

Figure 10 Comparison of the ultimate pit for bench height of 10- and 20-meter; (a) vein deposit; (b) massive deposit.

The bench and ramp widths were determined based on the selected loading and haulage equipment for each scenario. Since the size of the optimum pit is different, the road distance has a slight change. Therefore, the transportation cost was adjusted based on the haulage distance. Figure 10 shows the difference in pit size for bench heights of 10 and 20 meters for both deposits.

6. BENCH HEIGHT AND PRODUCTION PLANNING

In order to conduct an economic evaluation, a long-term production plan was implemented for each ultimate pit limit, determining the quantity of material to be extracted and calculating costs and revenues over each period. Defining the production rate is crucial for estimating equipment requirements, developing the long-term production plan, and conducting the economic evaluation of the project. Achieving a higher production rate generally leads to reduced operating costs, maximizing the Net Present Value of ore extraction despite a shorter mine life. However, pursuing higher production rates necessitates greater capital investment due to the need for larger equipment and infrastructure.

Table 5 Optimum pit characteristics for different scenarios

Parameter	Vein deposit			Massive deposit		
Bench height (m)	10	15	20	10	15	20
Total ore in pit (Kton)	106,010	117,690	122,236	629,099	644,405	656,292
Average grade (%)	1.02	0.93	0.9	0.59	0.58	0.58
Strip ratio	5.84	5.51	5.63	1.24	1.32	1.45
Metal content (Kton)	1,081	1,095	1,100	3.712	3,738	3,806

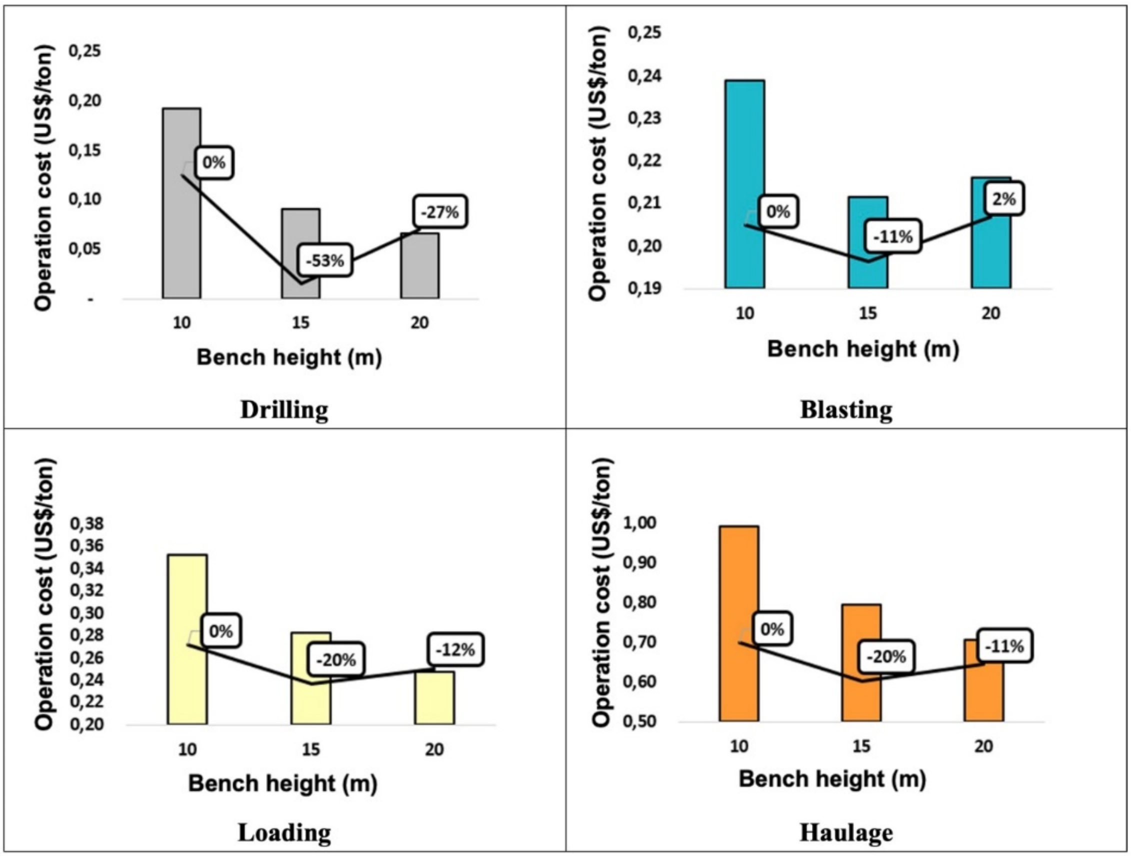

Figure 11 Percentage of changes in the cost of unit operation by increasing the bench height

Several scholars have addressed the challenge of estimating production rates. One commonly used approach is Taylor's rule, which empirically calculates the capacity and mine life for a given deposit (Taylor, 1986). Abdel Sabour (2002) identified a concave relationship between the cost of capital and the optimal mine size. Long (2009) established a new correlation between reserves and mine capacities. Wellmer & Drobe (2019) investigated the applicability of rules of thumb, specifically Taylor's Rule and Long's derived relationship, in assessing the economic feasibility of mines. Their findings supported the use of Long's method (Long, 2009), which demonstrated strong alignment with real-world data, for predictive economic evaluations during the exploration stageIn this research, instead of utilizing a single method to define the production rate, multiple production rate options were explored for each scenario, allowing for the calculation of mine life and equipment requirements.

7. RESULTS AND DISCUSSION

After the main equipment and operational design of the pits were defined, the operational cost of different unit operations was obtained for each bench height in the vein and massive deposits. Although the intersection point of the mining ramp and topography was kept the same for all cases, the ramp profile and distance were changed, especially for the two types of deposits, due to differences in deposit size and depth of the optimum pit. Therefore, among the unit operations, only the transportation cost was changed for the two deposits. However, the percentage of changes in haulage cost due to increasing the bench height was almost the same for both deposits.

The percentage change in unit operation cost for varying bench heights is shown in Figure 11. From Figure 11, it can be seen that drilling costs have more significant changes when the bench height is increased. Changes in operational cost were more significant when the bench height was increased from 10 to 15 meters compared to an increase from 15 to 20 meters. In general, the cost decreases with an increase in bench height from 15 to 20 meters, except in the case of blasting cost, where a 2% increase is observed (Figure 11). This could be due to an increase in explosive material.

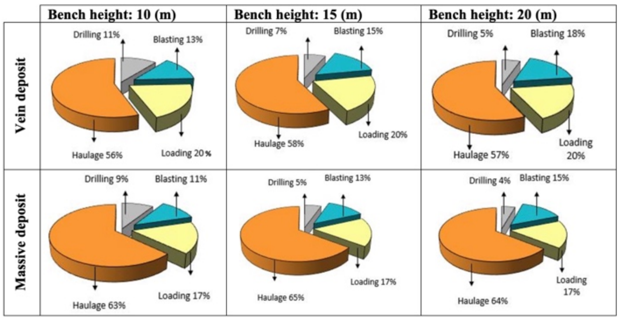

Figure 12 Percentage of unit operating costs for each type of deposit

Figure 12 shows the breakdown of operational costs for each unit operation in both types of deposits. In all scenarios, haulage costs have the highest percentage of the total cost, followed by loading, blasting, and drilling costs. It's worth noting that the contribution of loading costs remains unchanged despite increasing the bench height. Although the percentage of drilling operation costs decreases as the bench height increases for both deposits, the blasting portion of the cost increases for higher benches. Additionally, due to the road layout, the transportation costs have the highest contribution to the total cost when the bench height is 15 meters.

An economic evaluation of a strategic production plan for different bench heights showed that the effect of this parameter could vary by changing the production rate of ore material. Figures 13 and 14 illustrate the economic evaluation for the vein and massive deposits, respectively. These graphs were generated by creating strategic mine plans for each production rate scenario, followed by an economic evaluation for each production plan.

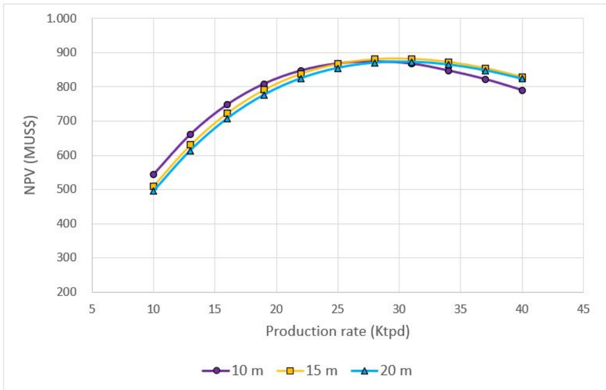

Figure 13 Economic evaluation of the vein type of deposit

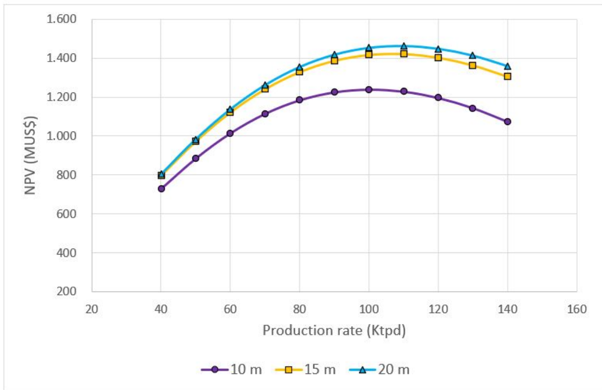

Figure 14 Economic evaluation of the massive type of deposit

Figure 13 shows that, a bench height of 10 meters results in a higher net value when the production rate is less than 25K tons per hour (for this specific vein deposit), despite having the highest operational cost. This is due to the higher selectivity and lower dilution when selecting shorter benches in vein deposits. In addition, a lower production rate results in lower investment costs since a smaller amount of material needs to be handled and processed. When the production rate increases, a bench height of 15 meters yields a higher NPV (882.4MUS$) for 13 years. A bench height of 20 meters is not recommended under any production rate for vein deposits since it always presents a lower net value than the other scenarios. In this case, the operational cost savings due to larger bench heights do not offset the negative effects of dilution and high capital costs.

In the case of massive deposit, a range of production rates from 40 ktph to 140 ktph were analysed for different bench heights. Figure 14 shows that the net present value of the 10-meter bench scenario is significantly lower than the other bench heights. However, a 20-meter bench height generates the most NPV at all production rates, reaching an optimum of 110 ktpd with a mine life of 20 years.

Although for production rates up to 60 ktpd, the economic results for the 15-meter and 20-meter bench heights are almost similar, the difference in NPV between these two bench heights becomes more noticeable as the production rates increase. This observation can be explained by the fact that for lower production rates, the operational cost savings from using a 20-meter bench height are not enough to compensate for the higher capital cost. However, as the production rate increases, it can be observed that the 20-meter bench height yields a somewhat higher NPV in comparison with the 15-meter bench height. Despite that small gain in NPV that occurs under those higher rates, the operational cost savings from using a 20-meter bench height is not sufficient to justify the higher capital costs. Therefore, for this deposit, a 15-meter bench height is preferred since the lower capital cost and greater operational flexibility will reduce the financial risk of the project.

8. CONCLUSION

This paper analyzes the effect of bench height on mining costs and economic evaluation, taking into consideration the production rate and shape of the deposit. To achieve this, different scenarios of bench heights and production rates were defined for two types of copper deposits: vein and massive. After comparing the results, it was concluded that as bench height increases, there is an impact on selectivity and dilution, leading to an increase in ore tonnage and a reduction in the average grade. However, the magnitude of this effect depends on the nature and geometry of the deposit and is much more significant in vein-type or selective deposits.

Our analysis also showed that bench height influences the selection of drilling, loading, and haulage equipment. To minimize capital and operational costs, the size and quantity of the required equipment should be modified according to the bench height. Even though the capital cost of bigger equipment is higher, the operational cost showed a clear tendency to decrease when greater bench heights are selected. However, in blasting, although increasing bench height results in wider drill patterns, which allow for a greater volume of rock to be removed per hole, the specific charge of explosives begins to increase for bench heights over 15 meters, generating an increase in costs. Conversely, drilling costs reduced with increasing bench height.

Mine planning and optimization depend on initial assumptions of mining costs, but once a bench height is chosen, selecting equipment or having a well-formed idea of equipment is crucial to accurately estimate capital and operational costs. Although higher bench heights increase the probability of dilution, selecting larger equipment leads to lower operational costs and allows for a larger final pit. Therefore, it is important to carefully consider the relationship between bench height and equipment selection when estimating mining costs and optimizing mine plans.The economic evaluation of the vein-type deposit revealed that for a production rate below 25 Ktpd, a 10-meter bench height was the best option, despite providing a lower net value than a 15-meter bench height, which offered a maximum net value 1.7% higher. When deciding between a 10-meter or 15-meter bench, it is essential to consider the risk of higher capital costs for investors and reduced operational flexibility. Therefore, from a conservative standpoint, increasing bench height above 10 meters for this type of deposit is undesirable. The negative impact of dilution when using larger bench heights and the higher capital cost of equipment outweigh the benefits of lower operational costs. In other words, selecting large bench heights and high production rates resulted in a decreased net value for this type of deposit.

In contrast, for massive deposits, selecting large bench heights increases the net value since there is no significant effect of dilution. The possibility of using larger equipment for higher benches reduces operating costs and offsets capital costs. The trend of net value and production rate for different bench heights showed that for massive deposits, there is no significant difference between the NPV of 15-meter and 20-meter bench heights when the production rate is less than 60 Ktpd. Generally, the results of NPV evaluation for both deposits indicate that when dilution and mine selectivity are not significant factors, the selection of bench height depends primarily on the production rate, and higher benches are preferable as production rates increase.

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