

Optimized Method of Estimating Mineral Reserves Using the O'Hara Mathematical Model for Underground Mining in Peru

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Abstract. This research project is aimed at applying the proposed methodology to optimize the calculation of mining reserves using an empirical relationship for dilution, as proposed by O'Hara. This methodology uses three key parameters: dilution, mineral value, and total costs. In general, costs include mining costs, processing within plants, and administrative expenses related to producing a mineralized block. Similarly, to calculate the mineral value, studies on changes in mineral prices over the last 30 years were included to provide more representative values. The research was applied to mineralized block number 1000, which yielded positive results since dilution could be easily calculated using three key parameters: operating method, dip, and vein width. The dilution value of 12.25% was valid, as it was within the range of 10% to 23%. This range was considered based on other studies that apply this operating method. Then, the methodology was analyzed in three more settings, each represented by a mineralized block. The blocks assessed were 1001, 1002, and 1003, and the results indicated that the dilution found was acceptable at values of 18%, 19%, and 22%, respectively.

1. Introduction

Estimating mineral reserves in marginal resources is of utmost importance for a mining company because materials deemed below the cutoff grade could become mineral reserves in the future. According to [1], in the international context where prices increase, not only would proven reserves start producing higher production volumes but also work in probable reserve areas would be justified.

This research proposes using a methodology that can validate the change from a mineralized resource to a mineral reserve. For these purposes, the three key parameters used are cutoff grade, international price of the mineral ore, and dilution. However, the dilution parameter may vary depending on the method used for its calculation. For example, [2] developed an empirical method where dilution directly depended on the mining method, stope width, dip angle, and rock's competence. [3] proposes an empirical method based on gathering information from different mines, [4] studies a variation of the Mathews stability graph method, and concludes that the higher the stability, the lower is the dilution.

Within this context, this research study seeks to propose a method that simplifies dilution calculation in order to estimate mining reserves, considering the main parameters of vein thickness, dip, operating



method, and wall competence. Obtaining dilution can be associated with the NSR cutoff grade and the mineral ore's economic value to verify if the block is considered a mineral resource or reserve.

2. State of the art

2.1. Estimating Reserves

Mineral reserves are the economically exploitable part of a measured or indicated mineral resource. According to [5], mineral ore's value is an essential assessment factor in the short, medium, and long term, because it is the only factor that companies selling the mineral cannot directly control.

According to [6], the level of influence of the reserves calculated based on geological models improves the management of mining cycle processes with precision of the extracted mineral ore's uniform grade.

2.2. Calculating Classic Dilution and Using Mining Software

When assessing mining reserves, it is necessary to understand some geological parameters specific to each operating method. The dilution present during blasting and transporting minerals is one of them. As stated by [7], the processing costs of the diluted material can range from USD 30 to 40 per ton.

The method proposed by O'Hara can be used graphically and mathematically by applying the formula that was developed, which points to a more exact value.

2.3. Cutoff Grade and Operating Costs

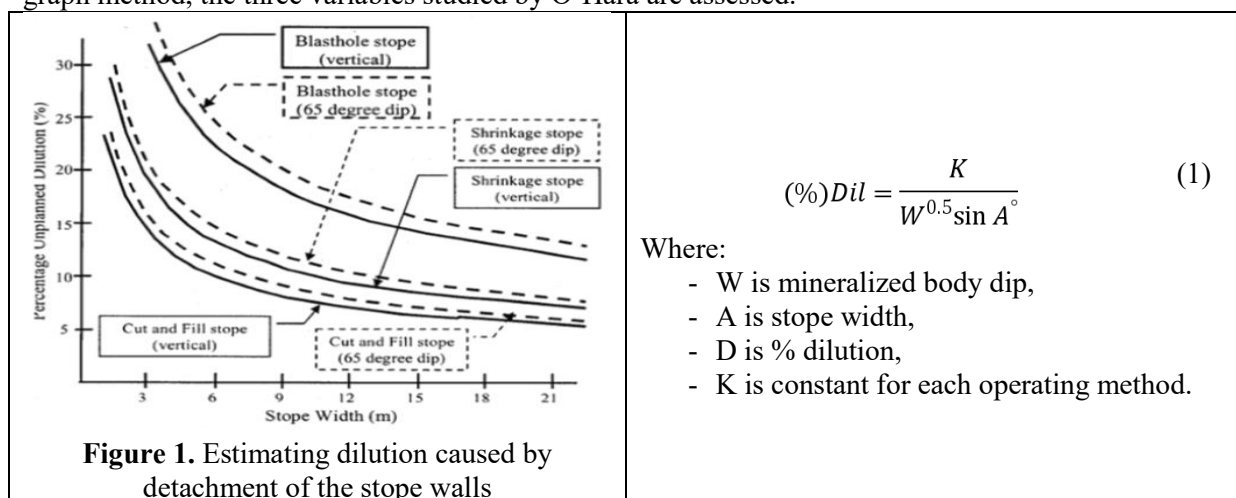
The secondary grade, also known as operational grade, is below the cutoff grade but related to sterile material. The secondary material is not taken to the dump site but stored in specially designed places for future treatment. Estimating costs is a very important factor taken into account by [8], [9], and [10] when it comes to creating value, because this parameter is compared to the mineral ore's value and helps determine if the business is profitable or not. As noted by [11], the costs that should be assessed during an economic analysis concern preparation, operating, mining, processing, energy, and administrative.

3. Contribution

3.1. Proposed Method

The reserve calculation method proposed begins by calculating the dilution, continues by determining the mineral ore's value, and develops the NSR cutoff grade.

As mentioned earlier, the dilution method we are putting into practice is from O'Hara. This empirical method can be applied graphically (Figure 1) or mathematically (Equation 1). In order to apply the graph method, the three variables studied by O'Hara are assessed.



The first variable, and the most general, is the operating method that the mining unit uses. In Fig. 1, the operating method is represented using different curves, which include four operating methods: cut and fill, shrinkage, room and pillar, and blasthole. The second variable is the stope width. In Fig. 1, the horizontal axis is the stope width variable, which is assessed in feet. The third variable is the dip angle of the mineralized body. In Fig. 1, the dip angle varies depending on the operating method, and there are two curves: one for a vertical angle or 90-degree dip and another for a minimum of 65 degrees.

When the mathematical formula is applied (1) (Empirical formula to find the O'Hara dilution), a similar reasoning is followed, since the formula is a mathematical adjustment of the graph. Its three variables are as follows: dip angle of the body, operating method, and stope width. The only difference is that in the formula, the operating method is connected using the K parameter, which is a factor included in the formula according to each method: cut and fill=45, shrinkage=60, room and pillar=70, blasthole=100.

Once the dilution is obtained, the mineral ore's value is assessed using (2) (Calculating mineral value in polymetallic mines). Two parameters are necessary for this calculation: diluted grade and mineral factor. The diluted grade can be found quickly using (3) (Diluted grade equation), where the grade is multiplied by geological tonnage and divided by geological tonnage plus tons of waste.

$$VM = \text{diluted grade (Cu)} \times FM \text{ (Cu)} + \text{diluted grade (Pb)} \times FM \text{ (Pb)} + \text{diluted grade (Ag)} \times FM \text{ (Ag)} + \text{diluted grade (Zn)} \times FM \text{ (Zn)} \quad (2)$$

$$\text{Dil. grade} = \frac{\text{Grade} \times \text{geological tonnage}}{\text{Geological tonnage} + \text{waste tonnage}} \quad (3)$$

As the last step, the NSR cutoff grade is assessed (4) (Cost equation applied for underground mining), which is understood as the sum of all costs from the different operations during the mining and processing cycle.

$$\text{Cost} = \text{mining cost} + \text{cost} \frac{\text{profits}}{\text{processing}} + G.A \quad (4)$$

In the practical sense, the methodology below is the following: if the mineral value is less than the NSR cutoff grade, the block is considered not to have economic value; if the mineral value is greater than 1.5 times the cutoff grade, it is considered economically valuable; and if it is greater than the NSR cutoff grade but less than 1.5 times, it is considered marginal material.

Finally, the methodology to be followed is summarized in Figure 2.

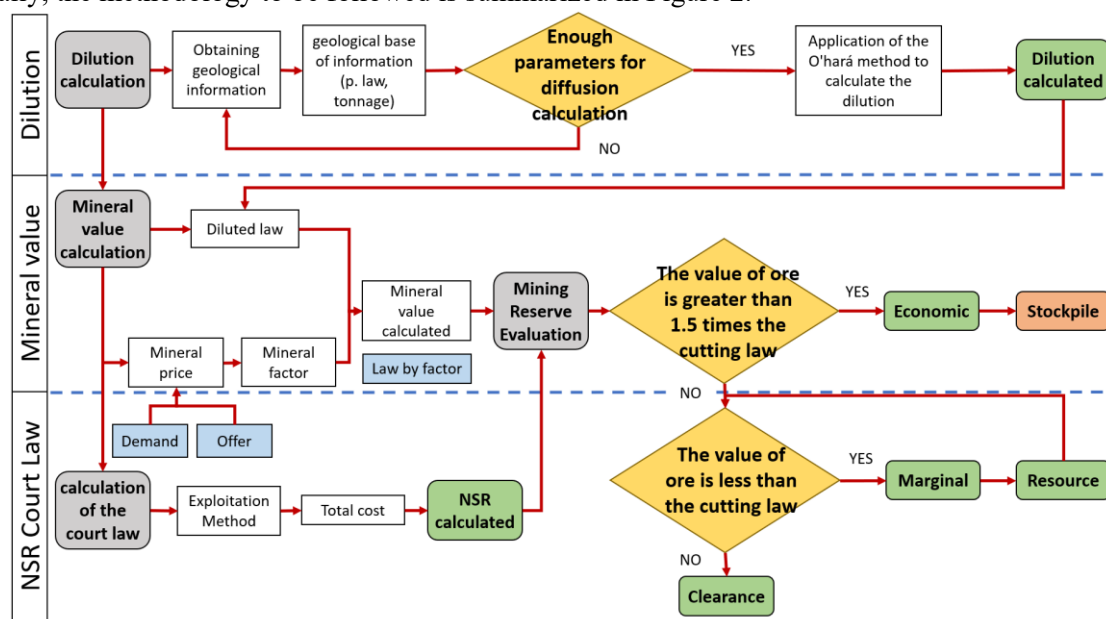


Figure 2. Process for estimating mineral reserves using the classic method

3.2. Results Indicators

The indicators to measure the results are based on the three stages of the proposed method: dilution, mineral value, and NSR cutoff grade. Thus, they are quantitative results of the mineralized reserve estimates. The three indicators to be measured and their corresponding units of measurement are presented below: The dilution percentage found in each mineral block, The mineral ore's economic value (USD/MT), NSR cutoff grade (USD/MT).

4. Validation

4.1. Study Area

The case study where the research was conducted is the mining company Raura, has an existing capacity of 2,000 tons per day. The Raura mining deposit is located between the Departments of Huánuco, Lima, and Pasco. The medium-sized underground mining company specializes in mining copper, lead, silver, and zinc minerals (polymetallic), and obtaining copper, lead, and zinc concentrates.

4.2. Initial Assessment

Using the initial calculation, block 1000 had values similar to those obtained by the proposed method; however, the two indicators that changed the most were the dilution percentage and the mineral ore's economic value shown in dollars per ton. In Table 1, the parameters mentioned can be identified.

4.3. Results from the Applied Method

First, after applying the O'Hara formula, a dilution of 12.25% was found for block 1000 from the Veronica Vein. This value was found using the methodology proposed by O'Hara. The values of the parameters: $K = 24$, 75-degree dip and vein thickness = 4.26 feet.

Second, the mineral value for block 1000 was found. The diluted grades are as follows: 2.72 oz/MT silver, 0.33% copper, 2.76% lead, and 8.31% zinc. Diluted grades are the product of multiplying geological grades by the dilution level obtained, in this case by 12.25%.

The resulting NSR cutoff grade was USD 77 per ton. The area with the highest costs is the area related to mining. The main costs are maintenance, operating, transportation, loading and hauling, and preparation, with almost 78% of the total (USD 35.84 per ton). The second highest area is general mining services. Its main costs are maintenance and energy, environment, and geology, which is 71% of the total (USD 14.35 per ton).

Finally, observing the final results, the dilution percentage is 12.25%, the cutoff grade is still USD 77 per MT, and the mineral value amounts to USD 197.24 per MT. Another value that varies is the dollar value of the mineralized block, since it changes from USD 1,717,068 to USD 2,011,806 due to the variation in dilution (Table 2).

Table 1. Initial research indicators

Structure	Lode Veronica
Method	CRBR
Block	1000
%Dilution	15.59%
Cutting law (US\$/TMS)	77
Mineral value (US\$/TMS)	168.34
Block value (US\$)	S/. 1,717,068.00

Table 2. Final research indicators

Structure	Lode Veronica
Method	CRBR
Block	1000
%Dilution	12.25%
Cutting law (US\$/TMS)	77
Mineral value (US\$/TMS)	197.24
Block value (US\$)	S/. 2,011,806.17

The proposed method achieved its objective of optimizing the calculation of mineral reserves; however, more tests must be completed in different mineralized blocks to verify that different case studies will work, since this method was adapted to an underground mine in Peru with specific geological and geomechanically conditions. Statistical parameters such as the mean, median, and geometric mean were assessed as representative measurements of the blocks (Table 3).

As mentioned above, the blocks vary from 10% to 23%, which is considered an acceptable dilution according to the operating method. The three central tendency values of mean, median, and geometric

mean can be analyzed, which summarize the dilution values found in the four mineral blocks. The geometric average is the value that best represents the four blocks and has a value of 17.75%.

Table 3. Settings and final research indicators

Scenarios	Structure	Tons	%Dilution	Cutting law (US\$/TMS)	Mineral value (US\$/TMS)	Block value (US\$)
Block 1000	Lode Veronica	8,200	12.25%	76.77	208.98	1,713,629.49
Block 1001	Lode Veronica	10,200	18.94%	76.77	197.24	2,011,806.17
Block 1002	Lode Veronica	10,200	19.22%	76.77	196.78	2,007,106.72
Block 1003	Lode Veronica	20,900	22.24%	76.77	169.61	3,544,911.81
Mean		12,375	18.16%		193.15	2,319,363.55
Median		10,200	19.08%		197.01	2,009,456.45
Geometric mean		11,556	17.75%		192.59	2,225,459.74

5. Conclusions

The reserve estimate results confirm the validity of the proposed methodology. Using the O'Hara method generated an acceptable dilution of 10% to 23%, the average value being 18%. Applying the method estimated very high mineral values. Among them, block 1003 obtained a value of USD 3,544,911.81 due to its high tonnage and considerably high diluted grades. Compared with average block values of USD 2,319,363.55, it is clear that the block has an extremely high economic value. It would have been optimal to have costs for each block; however, it was used as a constant for this study because the four blocks were mined using the long drill (breasting) method. The cost in each case was USD 76.77 per MT.

The method has only been tested on a mineral body that has the same operating method in all its blocks, in addition to similar geological characteristics. However, the dilution formula's K parameter should be adjusted if the method is applied to another body or another section of mineral operations because the empirical values assigned in the literature are specific to the geology studied in each research study. It is not feasible to expect to use that parameter because Peru's geology differs significantly, so it would be appropriate to research adapting the K constant for underground polymetallic mines in Peru.

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