IDENTIFYING THE DIG LINES FOR ORE EXTRACTION IN THE CASE OF OPEN-PIT MINING

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ABSTRACT. Based on the implementation of the contemporary Blast Movement Monitoring markers (BMMs) for tracking the movement of ore boundaries in the volume of a blasted rock pile, the post-blast ore boundaries can be determined with a satisfying accuracy. The calculated and visualized post-blast ore boundaries can be used for determining and calculating the boundaries of the improved dig lines for each flitch in the post-blast bench. The purpose of the improved dig lines is to acquire a maximal volume of ore, while preserving the initial ore grades as much as possible by tolerating the excavation of some waste volumes. Following the new dig lines, the amount of ore dilution is minimal, while maintaining a low level of ore loss at the same time.

Keywords: BMMs, dig lines, losses, dilution

ОПРЕДЕЛЯНЕ НА ГРАНИЦИТЕ НА ДОБИВНИЯ БЛОК В УСЛОВИЯТА НА ОТКРИТ ДОБИВ НА РУДНИ ПОЛЕЗНИ ИЗКОПАЕМИ

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РЕЗЮМЕ. Въз основа на използването на съвременната BMM технология (Маркери за мониторинг на отместването на взривното поле) за проследяването на отместването на рудните зони в рамките на взривявания блок, сравнително точно могат да бъдат определени крайните им граници в обема на скалния развал след извършено взривяване. Използването на отместените граници на орудяванията може да послужи за определянето на границите на добивните блокове за всяко подстъпало в рамките на работното стъпало, като се цели в границите им максимално да бъде запазено средното съдържание за всяка рудна зона. По този начин може се минимизира обедняването на рудата и да се проследят загубите на полезен компонент при добива на руда.

Ключови думи: BMM датчици, добивен блок, загуби, обедняване

Introduction

Modern-day ore mining practices have started including more and more sophisticated methods for improving the ore grade control due to the ever-changing economical situation as well as the accelerated scientific and technical progress. Using samples from pre-blast and post-blast mining surfaces prove to be a rational and a reliable source of information for the ore zones and their grade estimates. However, this type of technology has the drawback that the information of ore zone grades may take too long to be acquired from the chemical laboratory, which leads to complex organization of the mining process. In-situ ray logging of ores also proves to be a quick way of getting a both for pre-blast and post-blast grade information from the mining surfaces. However, its drawback is that the margin of error is not always satisfactory. Therefore, these two practices should be combined whenever the mining companies has the chance in order to make more precise estimates (Konstantinov, 1997). Another alternative is using a different type of technology for ore grade estimation in post-blast ore strings. One such successful method around the world is the use of the so called Blast Movement Monitors (BMMs) from Blast Movement Technologies. The targeted types of ores which use this type of technology include gold, copper, lithium, iron ore, nickel, platinum, silver, uranium and zinc. So far this technology has reached 133 mining companies in 41 countries around the world (blastmovement.com).

Purpose of Blast movement monitors (BMMs)

In open-pit mining the ore and waste flows are a part of two key processes: 1) the formation of stockpiles with different ore grades which are later used for blending and achieving the targeted ore grade, required for the processing plant; 2) the formation of waste dumps for poor ore grades below the cut-off grade and for overburden. However certain ore and waste mislocations may occur due to the unknown places of the post-blast ore and waste zones. Figure 1 represents the three main types of ore and waste msilocations.

Blast movement monitors (BMMs) prove to be helpful for gathering information on how the ore strings have moved after production blasting and for pinpointing their approximate location in the blasted rock pile (Fig. 2). So far many case studies around the world from Blast Movement Technologies have shown that using the post-blast ore strings for dig lines the avoided ore misclassification and dilution ensure a better economic result reaching up to several thousands of USD per blast.

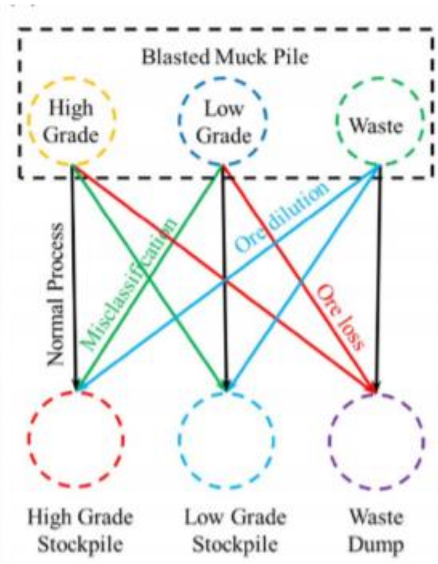

Fig. 1. The impact of blast-induced rock movement (Yu et al., 2019)

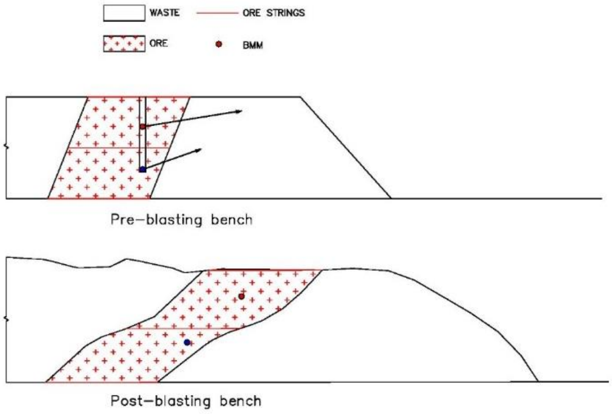

Fig. 2. The effect from using BMMs (ocblasting.com), (seequent.com)

Defining feasible dig lines using post-blast bmm ore strings

Most mining practices rely on using the same string boundaries as their dig lines. However, certain unwanted situations are likely to occur, which are not accounted for. These dig lines could lead to diluting the mined ore with overburden as well as realizing partial ore losses (Fig. 3).

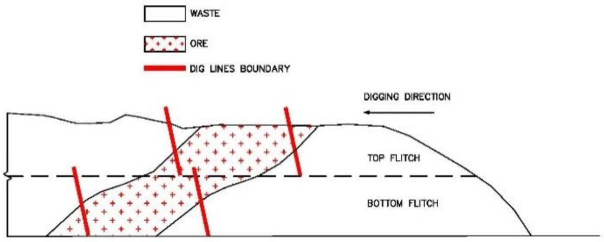

Fig. 3. Commonly used dig lines for each ore string (ocblasting.com), (seequent.com)

A different approach can be taken into consideration in order to properly define the dig lines for the post-blast ore strings. The strings regarding the same ore zone in the top flitch and the bottom flitch overlap each other in the view plane which lead to the formation of two main zones: 1) Inner Ore Zone (IOZ = TFS ∩ BFS) and 2) Outer Ore Zone (OOZ = TFZ ∪ BFZ) (Fig. 4).

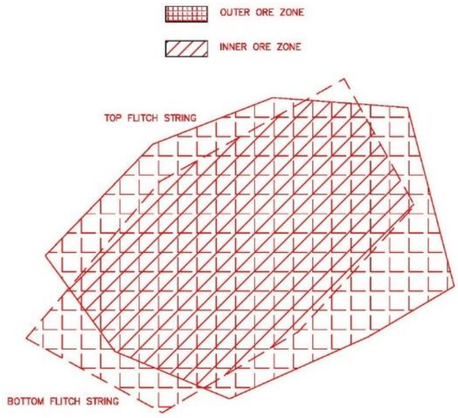

Fig. 4. Inner ore zone and Outer ore zone

One can notice that there are different zones inside the dig lines, where the ore remains with the same grade, while in other zones, the ore grade is diluted by the waste volumes. This required the Outer Ore Zone to be divided to certain elementary volumes (Fig. 5).

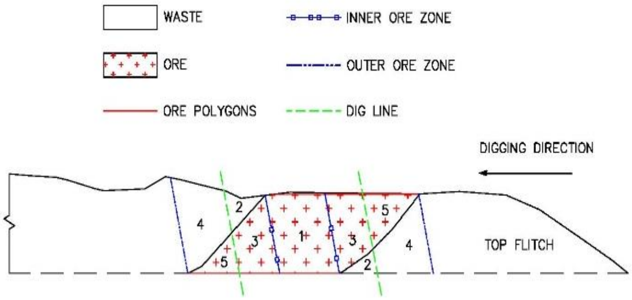

Fig. 5. Elementary volumes inside the Outer Ore zone

1 – $\boldsymbol{V_{i.o.z.}}$ – volume of ore in the Inner Ore Zone, m^3 (if the Top Flitch String and the Bottom Flitch strings do not overlap, TFS ∩ BFS = ∅, then $V_{i.o.z.} = 0$ m^3);
2 – $\boldsymbol{V^{o.b.}{}_{dil}}$ – volume of overburden from the diluted area outside the Inner Ore Zone, m^3;
3 – $\boldsymbol{V^{ore}{}_{dil}}$ – volume of ore from the diluted area outside the Inner Ore Zone, m^3;
4 – $\boldsymbol{V^{o.b.}{}_{loss}}$ - volume of overburden above or below the ore losses outside the dig lines, m^3;
5 – $\boldsymbol{V^{ore}{}_{loss}}$ – volume of ore losses outside the dig lines, m^3;

The figure shows that this method is applied for the top flitch. Nevertheless, the same logic could be applied while excavating the bottom flitch or mining the whole bench with its full height. In addition, the same logic can be applied for every string in the blasted rock pile.

The volume of the Outer Ore Zone inside the blasted rock pile can be represented with the equation:

$$V_{o.o.z.} = V_{i.o.z.} + V^{ore}{}_{dil.} + V^{o.b.}{}_{dil.} + V^{ore}{}_{mis.} + \\ + V^{o.b.}{}_{loss} + V^{ore}{}_{loss}$$

where $\boldsymbol{V_{o.o.z.}}$ – volume of each Outer Ore Zone, m^3;

$\boldsymbol{V^{ore}}_{\boldsymbol{mis.}}$ – volume of misclassified ore from neighboring ore strings inside the digging block boundary ($V^{ore}{}_{mis.}$ = 0 m^3 if there are no neighboring strings), m^3;

In general, the volume of the blasted area includes the volumes of ore from each string as well as the waste volumes in between the strings. After the blasting process is concluded the different elementary volumes preserve a weight balance. The volume of the post-blasted rock pile can be calculated the following way:

$$V_{b.r.p.} = V^{o.b.}{}_{b.r.p.} + \sum_{i=1}^{n} V_{o.o.z._i}$$

where $\boldsymbol{V_{b.r.p.}}$ – volume of blasted rock pile, m^3;

$\boldsymbol{V^{o.b.}}_{\boldsymbol{b.r.p.}}$ – volume of overburden in the blasted rock pile (outside every Outer Ore Zones), m^3;

$\boldsymbol{V_{o.o.z._i}}$ – volume of ore and overburden for Outer Ore Zone *i*, m^3;

i – sequential number for the Outer Ore Zones;

n – total number of Outer Ore Zones in the blasted rock pile;

The shape of the dig line boundaries depends on the ore strings geometry as well as the blast movement distance and direction. Another important factor is the excavator's digging direction. Nevertheless, the dig lines are used to identify whether the ore inside the dig lines are to be mined in a selective or bulk manner. There are three main goals which should be met in order to determine the optimal dig lines for each Outer Ore Zone:

1) a **maximum profit** should be achieved from the dig lines;

2) the **ore content for each dig block** should be either have a maximum value or it should not be lower than the initial category, in which the contents of ore strings belong to;

3) the **ore losses** should not be lower than an initially determined percentage;

In order to determine the dig line boundaries for each digging block a feasibility check has to be made in order to identify where it is feasible to excavate the diluted ore blocks and to determine whether the dilution is too high that it is more profitable to dilute and lose some of the post-blast ore via bulk mining. When applying selective mining the goal is to ensure a digging process where the blasted ore is excavated in its supposed contact zones with the overburden. Therefore, this ensures that the different elementary volumes of ore and overburden are transported to their correct place (stockpile for ores and waste dump for overburden).

The expected revenue for each blasted rock pile is determined by the two formulas for bulk and selective mining:

$$Revenue_{\,bulk\ i} = (V_{i.o.z.\ i} + V^{ore}{}_{dil.\ i} + V^{ore}{}_{mis.\ i}).\gamma_{ore}.P_m.\frac{\varepsilon}{100.\beta}$$

$$Revenue_{\,selective\ i} = (V_{i.o.z.\ i} + V^{ore}{}_{dil.\ i} + V^{ore}{}_{mis.\ i} + V^{ore}{}_{loss\ i}).\gamma_{ore}.P_m.\frac{\varepsilon}{100.\beta}$$

where $\boldsymbol{Revenue}_{\,\boldsymbol{bulk\,i}}$ – revenue from bulk mining technology for the Outer ore zone, USD (BGN);

$\boldsymbol{Revenue}_{\,\boldsymbol{selective\,i}}$ – revenue with from selective mining technology for the Outer ore zone, USD (BGN);

$\boldsymbol{\gamma_{ore}}$ – density of the ore, t/m^3;

$\boldsymbol{P_m}$ – metal price per ton, USD/t (BGN/t);

$\boldsymbol{\varepsilon}$ – percentage of concentrate extraction from the ore in the processing plant, %;

$\boldsymbol{\beta}$ – content of the metal product in the final processed concentrate, %

The costs for excavating each blasted rock pile includes the blasting costs, the excavation costs, transportation costs, ore processing costs and overburden waste dump building. Depending on the excavation technology (bulk or selective), the costs are determined by the formulas:

$$\begin{aligned}
Costs_{\,bulk} = {} & \\
& \left[\sum_{i=1}^{n} \gamma_{ore}.V_{i.o.z._i} + \gamma_{ore}.V^{ore}{}_{dil.\,i} + \gamma_{o.b.}.V^{o.b.}{}_{dil.\,i} + \gamma_{ore}.V^{ore}{}_{mis.\,i}\right].\left[L^{ore}.C^{ore}{}_{tr} + C_{pr}\right] + \\
& + \left[\gamma_{o.b.}.V^{o.b.}{}_{o.o.z.} + \sum_{i=1}^{n} \gamma_{ore}.V^{ore}{}_{loss\ i} + \gamma_{o.b.}.V^{o.b.}{}_{loss\ i}\right].L^{o.b.}.C^{o.b.}{}_{tr} + \\
& + \left[V^{o.b.}{}_{o.o.z.} + \sum_{i=1}^{n} V^{ore}{}_{loss\ i} + V^{o.b.}{}_{loss\ i}\right].C_{w.d.} + \\
& + V_{b.r.p.}.\left[C_{blast} + C_{exc}\right]
\end{aligned}$$

$$\begin{aligned}
Costs_{\,selective} = {} & \\
& \left[\sum_{i=1}^{n} V_{i.o.z._i} + V^{ore}{}_{dil.\,i} + V^{ore}{}_{loss.\,i} + V^{ore}{}_{mis.\,i}\right].\left[\gamma_{ore}.K^{\frac{s}{b}}{}_{tr}.L^{ore}.C^{ore}{}_{tr} + \gamma_{ore}.C_{pr}\right] + \\
& + \left[V^{o.b.}{}_{o.o.z.} + \sum_{i=1}^{n} V^{o.b.}{}_{dil\ i} + V^{o.b.}{}_{loss\ i}\right].\left[\gamma_{o.b.}.K^{\frac{s}{b}}{}_{tr}.L^{o.b.}.C^{o.b.}{}_{tr} + C_{w.d.}\right] + \\
& + V_{b.r.p.}.\left[C_{blast} + K^{\frac{s}{b}}{}_{exc}.C_{exc}\right]
\end{aligned}$$

where $\boldsymbol{\gamma_{o.b.}}$ – overburden density, t/m^3;
$\boldsymbol{C_{blast}}$ – blasting costs, USD/m^3 (BGN/m^3);
$\boldsymbol{C_{exc}}$ – excavation costs, USD/m^3 (BGN/m^3);
$\boldsymbol{L^{ore}}$ – distance for ore transportation, km;
$\boldsymbol{C^{ore}{}_{tr}}$ – relative costs for ore transportation, USD/t.km (BGN/t.km);
$\boldsymbol{C_{pr}}$ – relative ore processing costs, USD/t (BGN/t);
$\boldsymbol{L^{o.b.}}$ – distance for overburden transportation, km;
$\boldsymbol{C^{o.b.}{}_{tr}}$ - relative costs for overburden transportation, USD/t.km (BGN/t.km);
$\boldsymbol{C_{w.d.}}$ – relative costs for waste dump building, USD/m^3 (BGN/m^3);
$\boldsymbol{K^{\frac{s}{b}}{}_{exc}}$ – multiplier indicating how many times selective mining costs for excavation exceed the ones for bulk mining (due to preliminary operations of the excavator for moving overburden or ore volume aside);
$\boldsymbol{K^{\frac{s}{b}}{}_{tr}}$ - multiplier indicating how many times selective mining costs for transportation exceed the ones for bulk mining (due to idle time for trucks while waiting for the excavator).

The potential profit which every blasting generates can be calculated by subtracting the revenues and the costs respectively for bulk mining and selective mining.

$$Profit_{bulk_i} = Revenue_{bulk_i} - Costs_{bulk_i}$$
$$Profit_{selective_i} = Revenue_{selective_i} - Costs_{selective_i}$$

However, in order to determine whether it is feasible to excavate each mining block via a selective mining or bulk mining, the parameter Δ_i had to be defined to determine the difference between the profits from bulk mining to selective mining.

$$\Delta_i = Profit_{bulk_i} - Profit_{selective_i}$$

When $\Delta_i < 0$ selective mining is the more profitable alternative for the whole Outer Ore Zone. In this case each elementary volume is transported to its respective stockpile (for ore) or waste dump (for overburden). However, this may prove to be a very time-consuming and difficult task for the excavator's operator and his spotter and therefore it could be applied only in special occasions such as: 1) when the ore grade is high, 2) the grade estimation and the ore body geometry model is reliable, 3) the rock types for the ore and the overburden differ from each other visually, 4) the time-bound constraints are defined as a wide interval, etc.

When $\Delta_i > 0$ bulk mining is the more feasible type of mining technology for string *i* and the Outer Ore Zone is not fully mined. However, this could lead to unwanted ore losses and grade misclassification between neighboring ore strings. Hence, certain constraints have to be adopted in order to ensure the ore losses (OL$_{max}$) and dilution percentage (D$_{max}$) do not exceed a certain percent (Koprev, 2018):

$$1)\ \frac{V^{ore}{}_{loss\ i}}{V_{i.o.z._i} + V^{ore}{}_{dil.\ i} + V^{ore}{}_{mis.\ i} + V^{ore}{}_{loss\ i}} \leq OL_{\max i}$$

$$2)\ \frac{\gamma_{ore}\cdot(V^{in}{}_{d.b.\ i} + V^{ore}{}_{dil.} + V^{ore}{}_{mis.})}{\gamma_{ore}\cdot(V^{in}{}_{d.b.\ i} + V^{ore}{}_{dil.\ i} + V^{ore}{}_{mis.\ i}) + \gamma_{o.b.}\cdot V^{o.b.}{}_{dil.\ i}} \leq D_{\max i}$$

or

$$2)\ \frac{q_i\cdot\gamma_{ore}\cdot(V_{i.o.z._i} + V^{ore}{}_{dil.} + V^{ore}{}_{mis.})}{\gamma_{ore}\cdot(V_{i.o.z._i} + V^{ore}{}_{dil.\ i} + V^{ore}{}_{mis.\ i}) + \gamma_{o.b.}\cdot V^{o.b.}{}_{dil.\ i}} \rightarrow max$$

When $\Delta_i = 0$ both types of mining technology are equally feasible which leads to the need of preliminary adoption of further criteria, such as time-bound requirements for the selective mining technology as well as the levels of ore losses, misclassification and ore dilution.

Improving bulk and selective mining dig lines

Although these two alternatives seem to be simple and intuitive, they prove to be two totally opposite alternatives, which treat the content of every Outer Ore Zone either by achieving full selective mining (as much as possible) or full bulk mining. However, there is a third alternative which utilizes partial selectivity of the excavation process for each ore block. This could be achieved by dividing the outer dig lines in several inscribed boundaries which form halo-like zones of diluted ore around the Inner Ore Zone, which belong to one of the ore grade categories (Low Grade, Medium Grade, High Grade or Very High Grade) or fall into the zone below he cut-off grade (Fig. 6).

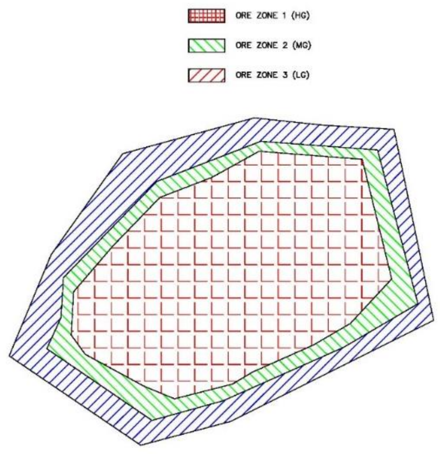

Fig. 6. Inscribed dig lines for the different ore zones deriving from the Inner and Outer Ore Zone boundaries

Following the excavation of the different ore zones from every Outer Ore Zone ensures that several volumes form with different grades of ore and they are separately transported and accumulated in their respective stockpile. Theoretically, this lowers the possibility of blending the ore while mining it and then mixing it once more with the ore grade from the stockpile, which could lead to misclassification in the respective stockpile. There are infinite number of solutions to this problem, so in order to reach satisfactory results, a heuristic approach is used for the solution. In order to achieve bigger volumes of higher grade ore, the innermost dig line assumes the lowest possible grade from the category of the inner boundary B$_{in}$. For example, if *q = MG (medium grade)*, then the ore grade for the first ore zone is $q^{MG}{}_{min}$. Generally, this could be written with the equation: $q^j = q^c{}_{min}$. This equation ensures that the content from the excavated ore inside the dig lines is not in a lower category than the initial ore content of the ore string.

Where q^j – ore grade for diluted ore zone *j*, % (or g/t);
j – consecutive number of the diluted ore zone (j ≥ 1);
$q^c{}_{min}$ – ore grade for ore category *c*, % (or g/t);
c - consecutive number of the ore grade category (c=1 is LG; c=2 is MG; c=3 is HG; c=4 VHG).

The following optimization function must be valid:

$$V^{in}{}_{d.b.\ ij} + V^{ore}{}_{dil.\ ij} + V^{ore}{}_{mis.\ ij} + V^{o.b.}{}_{dil.\ ij} \rightarrow max$$

while

$$\frac{q_i \cdot \gamma_{ore} \cdot (V_{i.o.z.ij} + V^{ore}{}_{mis.\ ij} + V^{ore}{}_{dil.\ ij})}{\gamma_{ore} \cdot (V_{i.o.z.ij} + V^{ore}{}_{dil.\ ij} + V^{ore}{}_{mis.\ ij}) + \gamma_{o.b.} \cdot V^{o.b.}{}_{dil.\ ij}} = \\ = q^{c}{}_{min}$$

The solution of the optimization problem is reached at the limit of the set and therefore the location of the dig lines are determined by solving the latter equation.

Let us define the volume of ore zone *j* as $V_{o.z\ ij}$, where

$$V_{o.z\ ij} = V_{i.o.z.ij} + V^{ore}{}_{mis.\ ij} + V^{ore}{}_{dil.\ ij} + V^{o.b.}{}_{dil.\ ij}$$

In order to ensure that the number of trucks, required for transporting this volume the following requirement has to be fulfilled:

$$n_{min}.E.K_{s.f.} \leq V_{o.z\ ij} \leq n_{max}.E.K_{s.f.}N_s$$

where $\boldsymbol{E}$ – capacity of the excavator shovel, m^3;
$\boldsymbol{N_s}$ – number of trucks, required for transporting the ore volume;
$\boldsymbol{K_{s.f.}}$ – swelling factor (dependent on the rock type);
$\boldsymbol{n_{min}}$ – minimum number of shovels, required for reaching the truck's capacity, m^3, (n_{min} = 4);
$\boldsymbol{n_{min}}$ – maximum number of shovels, required for reaching the truck's capacity, m^3, (n_{min}= 6) (Djobov, Koprev, 2017)

In addition, integer programming problem has to be solved in order to achieve an integer value for $\frac{V_{o.z.\ ij}}{K_{s.f.}}$. After the adjusted ore zone volume solution $V'_{o.z.\ ij}$ is determined, the dig lines have to be adjusted by finding out the value for the adjusted ore grade $q'^{c}{}_{min}$ from the equation:

$$q'^{c}{}_{min} = \frac{q_i \cdot \gamma_{ore} \cdot (V_{i.o.z.ij} + V^{ore}{}_{mis.\ ij} + V^{ore}{}_{dil.\ ij} - \partial^{ore}{}_{ij})}{\gamma_{ore} \cdot (V_{i.o.z.ij} + V^{ore}{}_{dil.\ ij} + V^{ore}{}_{mis.\ ij}) + \gamma_{o.b.} \cdot (V^{o.b.}{}_{dil.\ ij} - \partial^{ore}{}_{ij} - \partial^{o.b.}{}_{ij})}$$

where $\partial^{ore}{}_{ij} + \partial^{o.b.}{}_{ij} = V_{o.z.\ ij} - V'_{o.z.\ ij}$
$\boldsymbol{\partial^{ore}{}_{ij}}$- volume of subtracted ore for reaching the integer requirement, m^3;
$\boldsymbol{\partial^{o.b.}{}_{ij}}$ - volume of subtracted overburden for reaching the integer requirement, m^3.

In order to find out the geometric position of the dig lines- either of the approaches could be assumed – 1) representing the blasted volume of ore and waste as an approximation with smaller blocks; 2) geometric interpretation of the post blast ore zones with elementary figures (prisms, pyramids and tetrahedrons). In both cases the zones outside the Inner Ore Zone and inside the Outer Ore Zone are projected as an area in the view plane. When applying the dig lines there is a dependency between this area and the volume whose projection is the same area.

After solving the following equation, the dig lines for block z are considered to be adjusted.

This calculation is repeated until one of the two cases is reached:

1) Either there is no volume left from the outer dig line boundary and the last ore zone has a higher grade than its respective grade category,
2) or the current diluted ore zone has an ore grade which below the cut-off grade.

If case 1 is reached, then the algorithm stops and new dig lines can no longer be generated and the existing ones no longer have to adjusted.

If case 2 is reached, then the last amount of volume has to be added the volumes of either of the previous one, two, three or four zones until the sum reaches a grade equal to the value of LG ore content. After the previous volumes and borders are corrected, no new dig lines are generated, as well as the existing ones no longer have to adjusted.

This process has to repeated independently for every ore top and bottom string inside the blasted rock pile. Once the algorithm is repeated for every string and optimal dig lines have been generated, the optimal solution for the blasted rock pile has been reached, as the optimization problem is separable. The sequential operations for solving the dig lines problem are shown as a flowchart on Figures 7a and 7b.

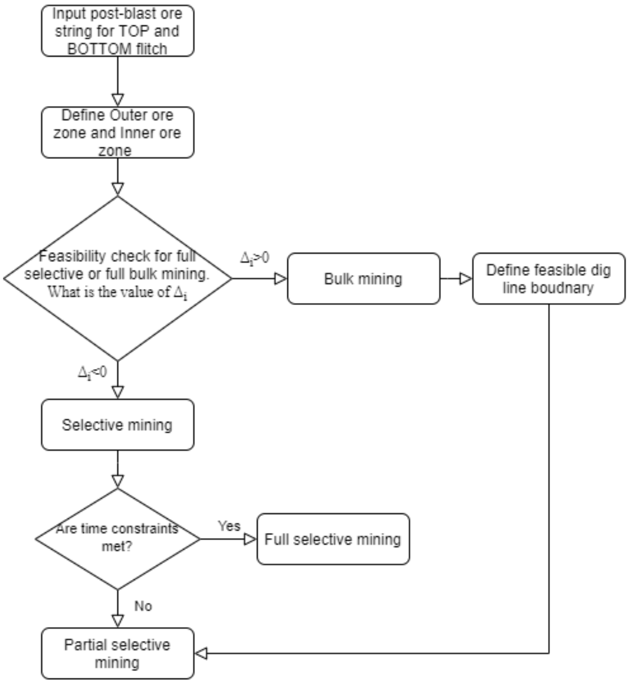

Fig. 7a. Flowchart of feasibility check for dig lines

This approach for solving the problem of differentiating the different dig lines for the different ore dilution/misclassification zone is also known as a "greedy algorithm" as it follows the problem-solving process of making locally optimal choices at each stage. Although this algorithm is not generally preferred, it serves a satisfactory job for the current problem, due to its ability to give the higher grade zones bigger volumes of ore, and the remaining volumes are considered either of low grade ore or below the cut-off. Therefore, the requirement for extracting the largest possible amount of volumes with higher ore grades is fulfilled.

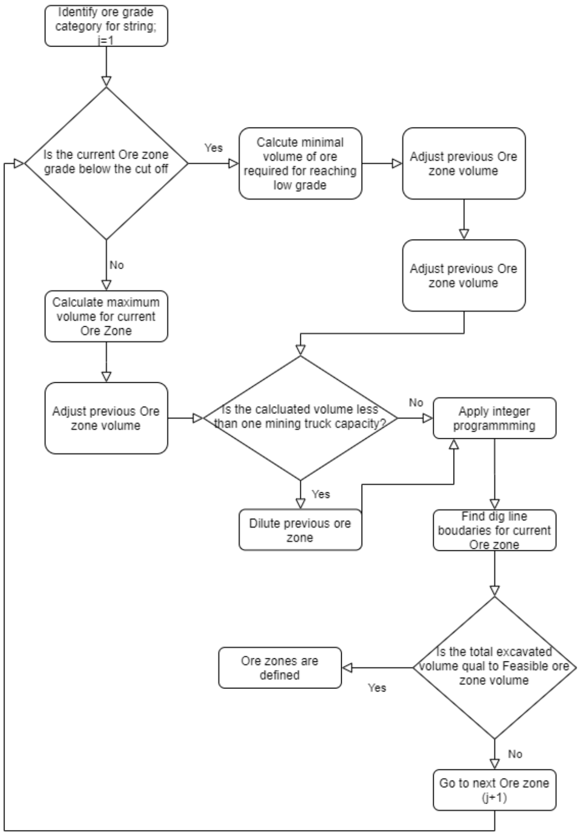

Fig. 7b. Flowchart of principles for defining lines for the partial selective ore mining

Conclusion

This paper serves as a theoretical examination of the feasible dig lines identification and has to be further examined by taking samples for chemical analysis and grade estimation from the supposed halo-like grade zones. A serious drawback of the proposed way for defining rational dig lines is that they are heavily dependent on the ore strings, defined by the geologists, the ore grade estimation for each string, as well as the string shape, the movement accounted by the BMM results and the digging direction. However, this way of ore excavation is expected to prove itself as more feasible than the currently used dig lines which follow the exact shape of the post-blast ore strings or flags markers distinguishing different ore grade zones.

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