Determination of the main parameters of Semi-level induced caving method with lateral loading

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Abstract: Exploring new mining methods in underground mining and proposing new, more perfect constructions of mining methods is a major challenge for all mining profession researchers. Large-scale mining methods are taking over the leading role in exploitation of low-grade and deep mineral deposits considering its high productivity, low cost, and satisfying ore recovery and ore dilution. In order to improve properties of existing block and sublevel caving methods, researches were carried out in laboratory conditions on physical model of similarity. Results of the research, the determination of optimal parameters and indicators for the new variant of the caving mining method is discussed in this paper. Experiments were based on ore drawing for the case with two and three one-sided lateral loading chambers and they were performed in order to determine the best combination between variable parameters of block width and spacing between loading chambers that would give the most optimal results for ore recovery and ore dilution (maximum ore recovery with minimal ore dilution).

Keywords: underground mining; block caving; sublevel caving; ore drawing; induced caving

1. Introduction

In current conditions of exploitation of ore deposits, when the content of useful components is decreasing more and more, and deposits fall to ever deeper depths, the need for application of high-productive mining methods is inevitability. Increasing production capacity reduces the costs of exploitation and enables economically profitable excavation of poor deposits. In the group of high-productive methods, the significant place is occupied by sublevel caving methods.

The high production capacities achieved by the use of caving methods are conditioned primarily by the possibility of complete mechanization of all production processes. The basic disadvantage of sublevel caving methods is the impossibility of a complete ore drawing, which is directly related to the dilution of ore. Higher ore recovery is achieved in its higher dilution, which entails higher costs of haulage, hoisting, and processing. This indicates that increasing of ore dilution is limited to the value when the total costs of exploitation and processing exceed the economic value of ore.

For successful and economical justified excavation an effective layout design and optimal drawpoint spacing are very important [1]. Process of ore drawing is essential for ore recovery and ore dilution and thus for success applying of mining method. For that reason, large number of researchers in recent years tried to determine a optimal spacing between drawpoints. That researches are mostly based on investigation of gravity flow, fragmentation size, etc. Julin and Tobie
[2] collected caving experiences worldwide and based on fragmentation from these data published a table to estimate spacing between drawpoints. Similarly to Julian and Tobie approach, Bullock and Hustrulid [3] used average fragment size to determine the radius of the isolated draw zone and further drawpoint spacing. Castro [4] used numerical model and flow simulator in order to predict gravity flow and determine parameters which would give maximal ore recovery with minimal ore dilution. At the Colorado School of Mines in the eighties of the last century, spacing between drawpoints were investigated on large two-dimensional models [5,6]. Truman and Susaeta used 3D physical model for ore drawing experiments [7-9].

Common to all researches is to deal with determining of drawpoint spacing, investigation of ore drawing process, designed excavation block with drawbells and regular schedule of excavation blocks. That’s why our research was directed to mining method construction with different position of excavation block, different position and number of loading chambers and bottom of block with trench undercutting.

In this paper, optimal parameters (drawpoint spacing and block width) for new construction of the mining method, which due to its specificity is called “Semi-level induced caving method with one-sided lateral loading”, is determined [10]. It can be classified as a group of caving methods and is used for mass excavation of ore. The study of the basic parameters of the mining method was carried out on physical similarity models in laboratory conditions.

2. Semi-level induced caving method

Semi-level induced caving method with one-sided lateral loading present one of the largest modification of applied mining methods from the group of sublevel caving.

This mining method, as well as numerous variants of sublevel caving, according to its characteristics and principles of excavation, belongs to a group of methods with ore and roof caving. It is well-known that mining methods in which the collapse of ore is carried out along the entire block height are called block mining methods. Block methods can be with self-caving (after the undercutting of the block, the rock mass starts to cave under its own weight) [11] or with induced caving (one-step or two-step). The considered method belongs to induced block caving method because collapsing of ore is over entire block height using drilling and blasting technology. However, with these methods, collapsing of ore can sometimes be carried out by blasting only from one level (by drilling the blast hole along the entire height of the block) when called level methods. In this case, ore collapsing is done by drilling from two levels, so the term semi-level is in the name of the method. Also, the term “semi-level” has been adopted because excavation blocks are “lowered” by the half of height of the horizon (level), so loading of the ore from the excavation block is done on each semi-level i.e. at levels with a height difference of 40 m.

In the Semi-level caving method, ore blasting is carried out in blocks of high altitude (40 m) and large thickness (24-42 m). Ore drawing is carried out from blocks width of 10-16 m and height equal to the height of the horizon. In that way, the conditions for achieving high productivity are created, which this method puts into the group of methods with mass ore extraction (large-scale mining methods).

The originality of the proposed construction of the Semi-level caving method is reflected in the fact that the ore is breaking down in high-altitude blocks, which is equal to the height of the horizon. The top of adjacent block is on the half of height in relation to previous excavation block. The following excavation block is on the same level as the first one, next on the same level as the other one, and this arrangement is repeated up to the end of the ore body [1]. This position of excavation blocks ensures that most of the blasted ore is located in the intact massive of ore, which significantly prolongs the period of pure ore drawing. This increases ore recovery and reduces ore dilution in the
drawing process, i.e. more favorable conditions for drawing of blasted ore are created, since the
lower half of the block does not have vertical contact with waste, except for the front contact of the
blasted area [12].

Breaking dawn of ore in the block will be done in the belts of great thickness. The construction
of the bottom of the block with lateral loading chambers enables simultaneously ore drawing along
the entire width of the blasted area. This kind of drawing enables a significant increase in the
production, increases the utilization of equipment on drilling, loading and hauling of ore, improves
the preparation dynamics for excavation [13].

With this method construction and the positioning of the transport drifts at the bottom of the
excavation block, the flow ventilation was enabled, which was one of the biggest disadvantage of the
sublevel caving. Auxiliary ventilation is applied only during facilities drivage in a development
phase.

In Figure 1, a variant of the Semi-level induced caving method with one-sided lateral loading is
shown.

![Figure 1. Semi-level induced caving method layout](image)

The alternate position of excavation blocks (see Figure 1), excavated and those that are in the
exploitation phase, does not suit the concentration of underground pressures. This is another
positive characteristic of the Semi-level induced caving, which makes it suitable for excavation of
large thickness ore deposits at great depths.

The axonometric view of excavation block model for Semi-level induced caving method is
shown on Figure 2.
Figure 2. Axonometric view of excavation block for Semi-level induced caving method with lateral loading

3. Experimental methodology

3.1. Physical model researches – the ore drawing

The ore drawing experiments were carried out on the physical model M-1 for the case with two and three one-sided lateral loading chambers in Laboratory for Underground mining methods at Technical Faculty in Bor, University of Belgrade. The model is made of plexiglass in scale 1:100 (Figure 3).
The results obtained from the performed experiments are shown in Table 1 and graphs of functional interdependence are formed based on the calculated values of ore recovery and ore dilution.

Conducted laboratory experiments, which are in the basis of this paper, were carried out in several stages – series.

1. Stage one – preliminary testing

For the proposed construction of the mining method, it was necessary to determine the appropriate geometric parameters. Variable parameters were: excavation block width (B), spacing between lateral loading chambers (l), and thickness of blasted ore \( (n \times m) \), where is \( n \) – number of loading rooms (chambers).

Block height (level height or double semi-level height \( (H= 2h = 80 \text{ m}) \) during all series of tests was set to 80 m since this height was suitable as the level height.

2. Stage two - the first series of tests

Figure 3. Physical model M-1
Based on preliminary testing and determining the shape of the draw body (flow ellipsoid eccentricity) [4], the limits of variable parameters were defined. Each test was carried out for all possible combinations of variable parameters and repeated three times.

3. Stage three – the second series of tests

The pairs of tested parameters with unsatisfying results were excluded from further testing. Analyzing obtained results it was determined that the results on the model M-1, for 8 m spacing between lateral loading chambers were much worse for any block width of 12, 14 and, 16 m than the results for 10 and 12 m spacing, regardless of the block width.

For parameters with satisfying results, tests were continued. Further tests were carried out with two draw points on model M-1. These additional tests were made in order to confirm results from the first series of tests.

4. Stage four – the third series of tests

In these last series of tests, experiments with parameters that provided the best relations between ore recovery and ore dilution were repeated. These experiments included inserting of 175 markers into physical model M-1 [10]. Embedded markers provide very precise interpretation of the results in analyses of drawing as well as the occurrences that happen in the model during the tests.

Ore drawing was carried out in specified doses, from the all loading chambers respectively. The first dose is drawdown until the appearance of waste in one of the loading chambers. The first appearance of waste will be in the third loading chamber, which is logical because the third loading chamber has frontal contact with waste. The contact area is equal to the area of the blasted ore block. The following drawing doses were exactly 2.5 kg each (drawn equally from each chamber) until the waste appears in all remaining chambers. Drawing is continued to the moment when ore dilution in chambers (in a dose) passed over 50%. However, in almost every test, in order to provide more points for a more precisely graphical illustration of the relation between ore recovery and ore dilution, the ore drawing went little further.

Tables and graphs were created for interpretation of results. Obtained amount of bulk ore ($Q_{bo}$), pure ore ($Q_{po}$) and waste ($Q_{w}$) per kg of each dose, is given in the table for every single test including a detailed test balance. Also, the table shows their cumulative values, as well as values of ore recovery $O_r(\%)$ and ore dilution $O_d(\%)$, in the dose and in total.

Based on the obtained pure ore ($Q_{po}$) and the total amount of embedded ore in the model ($Q_o$), for each test, ore recovery was calculated. Ore recovery is defined as a quotient of pure ore and total ore [14].

$$O_r = \frac{Q_{po}}{Q_o} \cdot 100, \%$$

Total ore recovery is calculated as a ratio between the cumulative value of pure ore and total ore in model.

Ore dilution for each dose is presented as a ratio between an amount of waste and bulk ore in dose [14].

$$O_d = \frac{Q_{w}}{Q_{bo}} \cdot 100, \%$$
Total ore dilution is obtained from the relation between cumulative values of waste and bulk ore.

4. Results and discussion

4.1. Interpretation of the obtained results

Data obtained from tests for considered variant were partially written for each loading chamber and each dose, which enabled interpretation of the results in total for each test and partially for each draw point for all series of tests.

Considering large volume of interpretation material (total of 73 tests were made) [10], in this paper only the best values for tested parameters are given.

Interpretation of the results was given through tables and graphs. Tables show obtained results and calculated values for ore recovery and ore dilution, for a single performed test, in total and in draw dose. Based on these calculated values, the graphic for ore recovery and ore dilution were formed. Equations, which also represented the interdependence beside the graphs, were created based on minimum squares theory. Line correlation ratio was used to determine the accuracy of approximation, i.e. deviation of equation from the relation curve. The line correlation ratio determines the accuracy of the approximation of curves which are found by the equations of regression.

High values of correlation ratio show high accuracy of approximation of functions \( O_d = f (O_r) \) and \( O_{d'} = f (O_{r'}) \) with regression equation. This means that using equations is possible, with sufficient accuracy, to calculate ore dilution (\( O_d \)) if the value of ore recovery (\( O_r \)) is known, and vice versa.

The amount of drawn ore and waste were written by the draw points for all performed tests, which allows partial interpretation of the results by single draw points. Also, based on shown relations, it is possible to compare the obtained results depending on the position of drawpoints (loading chambers).

4.2. Analysis of the obtained results

According to the measured quantities of pure ore and waste in drawn doses, values of ore recovery and ore dilution were calculated for each dose and in total. The calculated values are presented graphically and functional dependencies are obtained.

Two series of tests were performed: The first series of tests with variable parameters on the physical model with three loading rooms (chambers), and the second series of tests with same variable parameters, but on the model with two loading rooms (chambers).

In the first series of tests on the model M-1, 27 experiments were made for three different values of block width (12, 14, and 16 m) and spacing between lateral loading chambers (8, 10, and 12 m). For each combination of variable parameters, the experiment was repeated three times.

All tests had performed in the same way, adhering to the all condition of similarity (geometric, kinematic and dynamic) [15,16], so that it had been possible to present the three repeated experiments for one combination of parameters with a representative one.

Comparing test results, it is concluded that the best values for ore recovery of 89.94% and ore dilution of 10.68% with quantity of pure ore over 22% are obtained for block height of 80 m, block width of 12 m and spacing between loading chambers (drawpoints) of 12 m [10]. Table 1 and Figure 4 show the average values of the obtained results.
Table 1. Ore drawing results from model M-1 for H= 80 m; B= 12 m; L= 12 m; Q_\text{r}= 57.20 \text{ kg (three draw points)}

<table>
<thead>
<tr>
<th>Draw dose</th>
<th>Obtained results</th>
<th>Cumulatively</th>
<th>Ore recovery</th>
<th>Ore dilution</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bulk ore Q_{\text{m}} [kg]</td>
<td>Clean ore Q [kg]</td>
<td>Waste Q [kg]</td>
<td>Bulk ore Q_{\text{m}} [kg]</td>
</tr>
<tr>
<td>I</td>
<td>12.63</td>
<td>12.63</td>
<td>0.00</td>
<td>12.63</td>
</tr>
<tr>
<td>II</td>
<td>7.50</td>
<td>7.36</td>
<td>0.14</td>
<td>20.13</td>
</tr>
<tr>
<td>III</td>
<td>7.50</td>
<td>7.24</td>
<td>0.26</td>
<td>27.63</td>
</tr>
<tr>
<td>IV</td>
<td>7.50</td>
<td>7.09</td>
<td>0.42</td>
<td>35.13</td>
</tr>
<tr>
<td>V</td>
<td>7.47</td>
<td>6.92</td>
<td>0.55</td>
<td>42.60</td>
</tr>
<tr>
<td>VI</td>
<td>7.50</td>
<td>6.09</td>
<td>1.41</td>
<td>50.10</td>
</tr>
<tr>
<td>VII</td>
<td>7.50</td>
<td>4.12</td>
<td>3.38</td>
<td>57.60</td>
</tr>
<tr>
<td>VIII</td>
<td>7.50</td>
<td>2.79</td>
<td>4.72</td>
<td>65.10</td>
</tr>
<tr>
<td>IX</td>
<td>7.50</td>
<td>1.52</td>
<td>5.99</td>
<td>72.60</td>
</tr>
<tr>
<td>X</td>
<td>7.50</td>
<td>0.76</td>
<td>6.74</td>
<td>80.10</td>
</tr>
<tr>
<td>Σ</td>
<td>80.10</td>
<td>56.51</td>
<td>23.59</td>
<td>-</td>
</tr>
</tbody>
</table>

Detailed analysis, based on data given in Table 1, shows that 57.20 kg of ore were embedded in the physical model. As ore, in experiments was used ore from ore body Borska Reka (the Republic of Serbia). The iron ore magnetite from Damnjan pit (the Republic of North Macedonia) was used as a waste. Fragmentation size (scale 1:100) and prepared amount of ore and waste, used in experiments are shown in Table 2.

Table 2. Fragmentation size and total amount of ore and waste used in experiments

<table>
<thead>
<tr>
<th>Fragmentation size [mm]</th>
<th>Ore</th>
<th>Waste</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>%</td>
<td>kg</td>
</tr>
<tr>
<td>+ 10.00</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>-10.00</td>
<td>+ 6.68</td>
<td>10</td>
</tr>
<tr>
<td>-6.68</td>
<td>+ 4.699</td>
<td>20</td>
</tr>
<tr>
<td>-4.699</td>
<td>+ 2.362</td>
<td>45</td>
</tr>
<tr>
<td>-2.362</td>
<td>+ 0.0</td>
<td>25</td>
</tr>
<tr>
<td>Σ</td>
<td>100</td>
<td>75.00</td>
</tr>
</tbody>
</table>

Based on preliminary experiments [13,17], determined dependence between basic parameters of flow ellipsoid and forecasted fragmentation of blasted ore [18,19], values of average diameter for blasted ore and waste are obtained.

Average pieces diameter of blasted ore and waste is calculated according to the formula [20]:

$$d_{av} = \frac{\sum d_i \cdot P_i}{100}, \text{ m}$$ (3)

where:

$$d_i = \frac{d_1 + d_2}{2}, \text{ m}$$ – average diameter of narrow particle size,
% – percentage participation of a single particle size.

Using data from Table 2 scaled values of average diameters for particle size for ore of 3.85 mm and for waste of 5.81 mm are obtained.

Ore drawing was carried out simultaneously, evenly from three drawpoints (three loading chambers). The first draw dose was carried out till the appearance of waste. The first appearance of waste was in the third drawpoint, since, in addition to this drawpoint, is the closest vertical contact with waste (Figure 1). The quantity of pure ore was 12.63 kg, which is 22.08% in relation to the total embedded quantity of ore. In the further process of ore drawing, uniform doses of bulk ore in amount of 7.50 kg were drawn. In draw dose VII, ore dilution was 45.07% which indicate to more intensive waste drawing in the next doses. A quantity of waste increases in bulk ore and in following doses has high values of 62.87%, 79.80%, and 89.87% which is not economical [21]. Drawing up to the final amounts of bulk ore, ore recovery of 98.78% and ore dilution of 29.45% is obtained. Obviously, there is a need to stop with ore drawing earlier, with less ore dilution, which will be determined by economic results [21].

The best results, maximum ore recovery, minimum ore dilution, with a satisfying amount of pure ore, for optimal parameters, are shown on graph of interdependence between ore recovery and ore dilution (Figure 4).

![Figure 4. Average values of obtained results for parameters: H= 80 m, B= 12 m, and l= 12 m](image)

The best results were obtained for a distance between lateral loading chambers of 12 m, for all variable block width parameters (12, 14, and 16 m) and in all combinations of parameters. Comparative results of a drawing are shown in Figure 5.
Figure 5. Ore drawing results for the first series of tests (with three loading chambers)

Values of parameters: H= 80 m, B= 12, 14 and 16 m and l= 12 m

Curves 1,2: B= 12; l=12m (1 in a dose; 2 in total)
Curves 3,4: B= 14m; l=12m (3 in a dose, 4 in total)
Curves 5,6: B=16m; l=12m (5 in a dose, 6 in total)

In the second series, tests were performed on physical model M-1 for the same values of the variable parameters, but with two drawpoints. Spacing between lateral loading chambers of 8 m was not considered due to the worst results in testing. Also in this series of tests, the most satisfying results were obtained for block width of 12 m and spacing between lateral loading chambers of 12 m, which confirmed the conclusions from the first series of tests.

Tests results (comparable to different block widths) obtained in the second series of tests, with two lateral loading chambers and spacing between them of 12 m, are shown in Figure 6.

Figure 6. Ore drawing results for the second series of tests (with two loading chambers)

Values of parameters: H= 80 m, B= 12,14 and 16 m and l= 12 m

Curves 1,2: B= 12; l=12m (1 in a dose; 2 in total)
Curves 3,4: B= 14m; l=12m (3 in a dose, 4 in total)
Curves 5,6: B=16m; l=12m (5 in a dose, 6 in total)
Based on experiments from the first and the second series of tests on model M-1, the best results are obtained for the largest examined spacing between loading chambers of 12 m and the lowest block width of 12 m. This indicates for the necessity to continue testing with different values of variable parameters, in order to determine the optimal parameters.

For that reason, in third series of tests additional experiments were made (with pairs of parameters B= 12 m; l= 14 m and B= 14 m; l= 14 m), as well as experiments with embedded markers. Comparing the new results with the best results from the previous series gave the final answer: optimal parameters for Semi-level induced caving method with one-sided lateral loading are block width (B) of 12 m and spacing between loading chambers (l) of 12 m, according to testing on physical model M-1. These values of parameters provide a maximum amount of pure ore and highest ore recovery with minimum ore dilution.

Comparative results from the first and the second series of tests (with two and three drawpoints), for the best-obtained values of parameters, are shown in Figure 7.

![Figure 7](image-url)  
**Figure 7.** Comparative results of ore drawing with two and three loading chambers for the best parameters relations (H=80 m, B= 12 m, l= 12 m)

Curve 1 – two loading chambers (in a dose); Curve 2 – three loading chambers (in a dose);
Curve 3 – two loading chambers (in total); Curve 4 – three loading chambers (in total)

Better results for the optimal parameters are obtained with a larger number of drawpoints. Curves 2 and 4 on graph showed in Figure 7, confirm these conclusions, whether functional dependencies are observed in single draw dose or in total. The most important thing in the drawing process from the large thickness ore bodies is disciplined work, which implies, above all, uniformity in the ore drawing from the active loading chambers (drawpoints).

During tests have performed, data on the quantities of drawn ore and waste are partially written for each loading chamber, which enables the possibility for interpretation of the results by the draw points.

Based on the quantities of drawn ore and waste, it is possible to see how ore recovery and ore dilution change their values depending on the position of the drawpoints. For the best values of the parameters, the comparative results of the drawing by the loading chambers (drawpoints) are shown in Figure 8.
Figure 8. Test results of ore drawing by the draw points

1,2 – third loading chamber (in dose and total); 3,4 – first loading chamber (in dose and total); 5,6 – second chamber (in dose and total).

It is obvious, based on the shown graphs, total and partial, that Semi-level induced caving method provides much better results with a larger number of drawpoints.

Analysis of the results by drawpoints (loading chambers) confirms positive effects of simultaneous ore drawing from model M-1 designed for new construction of Semi-level induced caving method with one-sided lateral loading. This analysis confirms all the advantages and recommendations for the geometric arrangement where the “lower” position of excavation blocks is dominated (in frontal cross-section), and the originality of the solution for ore drawing from every second excavation blocks. All of this contributes to a maximum reduction in the contact of the blasted pure ore and waste. With such construction of excavation, the ore is drawing about half the high of the level (40 m), in a larger number of drawpoints (two) and pure ore without dilution is obtained. First dose containing waste, is obtained from the third loading chamber as a result of a vertical frontal contact with caved waste. From the second and the first loading chamber, 65-80% of pure ore is obtained with maximum ore recovery (93-96%) and ore dilution of 10%.

The obvious advantages of this kind of drawing indicate that a larger amount of blasted ore is obtained related to the amount of ore which is geometrically located just above the drawpoint (Figure 8). Ore drawing should be stopped when waste from the horizontal contact and upper parts of excavation block has been drawndown to the loading level.

5. Conclusion

The new mining method design called Semi-level induced caving with one-sided lateral loading and determination of its optimal parameters was considered. The base characteristic of the designed mining method is in the collapsing of ore in high-altitude blocks, (matched with horizon height) which is same like the height of the horizon. The adjacent excavation blocks are “lowered” by the half of height of the horizon. This position of the excavation blocks provides a maximal reduction of the contact area between blasted ore and waste. This allows more favorable conditions for ore drawing and achieving much better indicators of drawing (larger quantity of pure ore and high ore recovery value with minimal ore dilution is obtained). Construction of the bottom of the excavation block allows flow ventilation for each block that is excavated.
Extensive laboratory tests, on the physical model of similarity, were performed in series for different variable parameters and for a different number of loading chambers in the simultaneous work. The results of testing are presented in tables and on the graphs.

Analyzing the results and comparing the obtained values, the best combination of parameters occurred. For the variant of the Semi-level induced caving method with one-sided lateral loading, obtained optimal parameters of excavation block width of 12 m, excavation block height of 80 m and spacing between lateral loading chambers of 12 m provide the most favorable mining method indicators (maximal quantity of pure ore of 22%, high ore recovery of 90%, minimal ore dilution of 10%).

In order to achieve high values for ore recovery, it is necessary to adhere with loading discipline from the loading chambers, i.e. the same or approximately the same amount of ore from all loading chambers.

In the tests for the considered variant of mining method, ore drawing was performed from two and three loading chambers. The relationship between the results indicates that it is necessary to work with a larger number of drawpoints. In this way, better effects are achieved, i.e. higher ore recovery is obtained.

In further research of proposed new mining method design, it is necessary to perform experimental excavation in the mine. This is next, a necessary phase in examining the possibility of applying Semi-level induced caving method. The need for field testing is in the fact, that all the influential factors could not be simulated in model testing. In the in situ researches, the principles of the mining method must be observed. Special attention must be paid to the ore drawing.

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