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Mining method optimisation of Bayi gold mine based on the value engineering principle

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Abstract

Bayi gold mine is located in the northeast of Habahe County, Altai city, Xinjiang autonomy region, China. There are No. 1 and No. 2 mining districts in the mine, of which No. 1 is the main production district. The group of 12# veins is the main orebody, of which the top veins over +610 m were mined out with the open pit mining method. The upper part of the remaining orebodies is mined underground with the short-hole shrinkage stoping method. However, at about +400 m level, those veins gradually merge into one 30–60-m thick orebody, hence the mining method for the lower thick orebody has to be changed. For safe mining, the backfill method has been suggested. In this paper, mining method selection was regarded as a system engineering problem with multi-objective decision-making. In the primary selection, three kinds of underground backfill mining methods were proposed. A comprehensive multi-objective decision-making index system for mining method optimisation was built up based on the value engineering principle, and technical feasibility, resources utilisation and economic benefit factors were taken in consideration for safe mining and environmental protection. In order to integrate the experts' experience and to put the original qualitative comparison into quantitative analysis, the comparative importance of the functional parameters decided by the 0–1 compulsory scoring method was introduced. Therefore, the functions and values of primary selected mining methods with unified multi-objective data for comparison were obtained. Based on that, the optimised mining method, i.e. sublevel open stoping with delayed backfill, was selected. The final optimised mining method was designed and put into stope preparation.

1 Introduction

Bayi gold mine is located in the northeast of Habahe County, Altai city, Xinjiang autonomy region, China. There are No. 1 and No. 2 mining districts in the mine, of which No. 1 is currently the main production district. The group of 12# veins is the main mining orebody, which is generally 30–40 m thick, 400–500 m long discontinuously, dipping 79–82° to the southwest 220°, with an average grade of 2 g/t, as schematically presented in Figure 1 (Zheng et al. 2010). The top veins, i.e. over +610 m level, were mined out with the open pit mining method. As the width of each vein is only 2–3 m, the upper veins, starting from +570 m level, are mined underground with short-hole shrinkage stoping method (Liu et al. 2015), as shown in Figure 2. However, at about +400 m level, those veins gradually merge into one thick orebody of 30–60 m in width, with a dipping angle of about 58°, hence, the mining method for the lower thick orebody has to be changed.

Aiming for safe mining, most mined out voids of the upper veins should be treated with backfill materials, and the backfill method has been suggested for mining of the lower thick orebody (Huang et al. 2015). Hence, a program of mining method optimisation and design has been carried out.

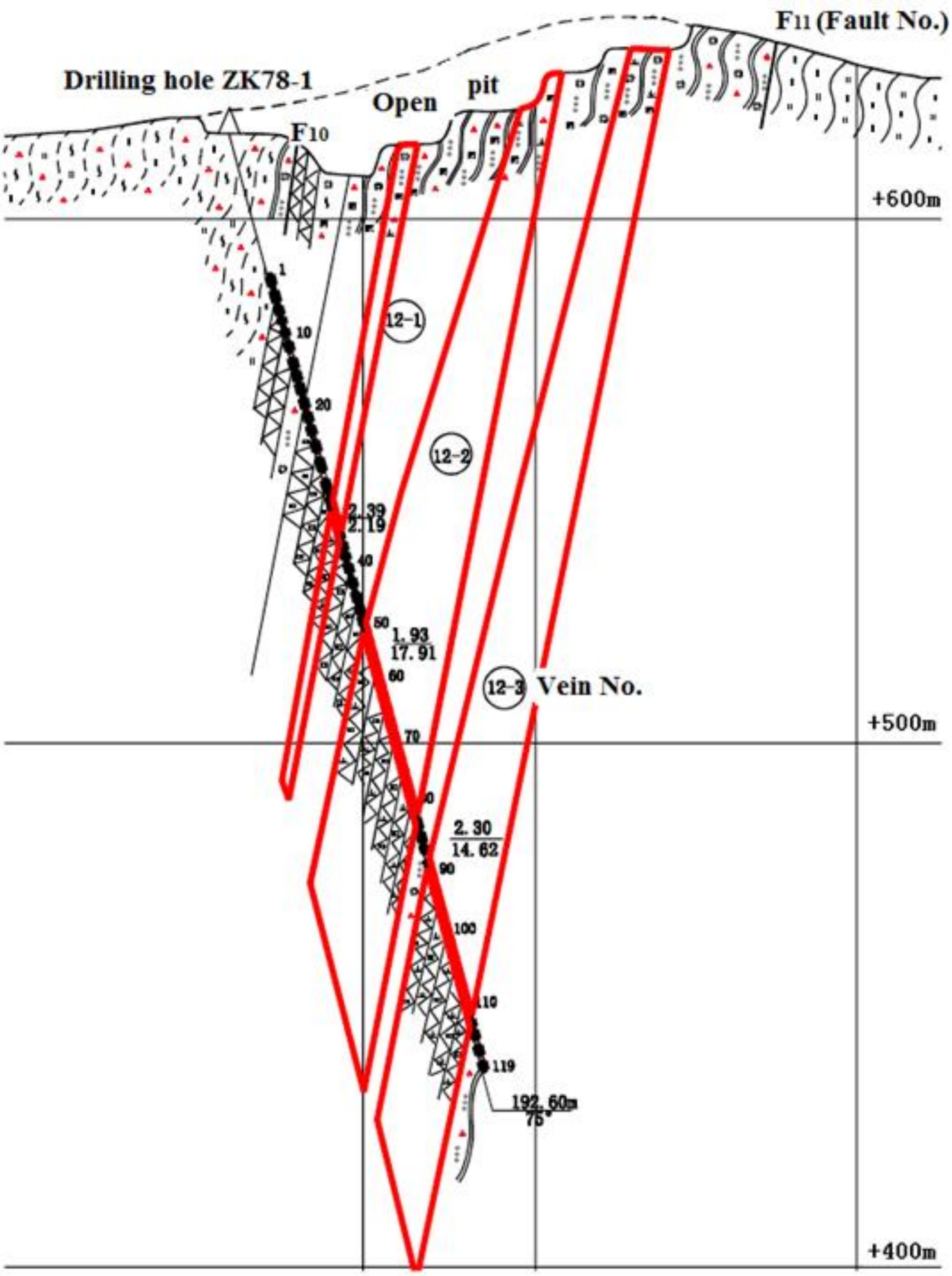

Figure 1 Section view of 12# veins in the No. 1 mining district of Bayi gold mine

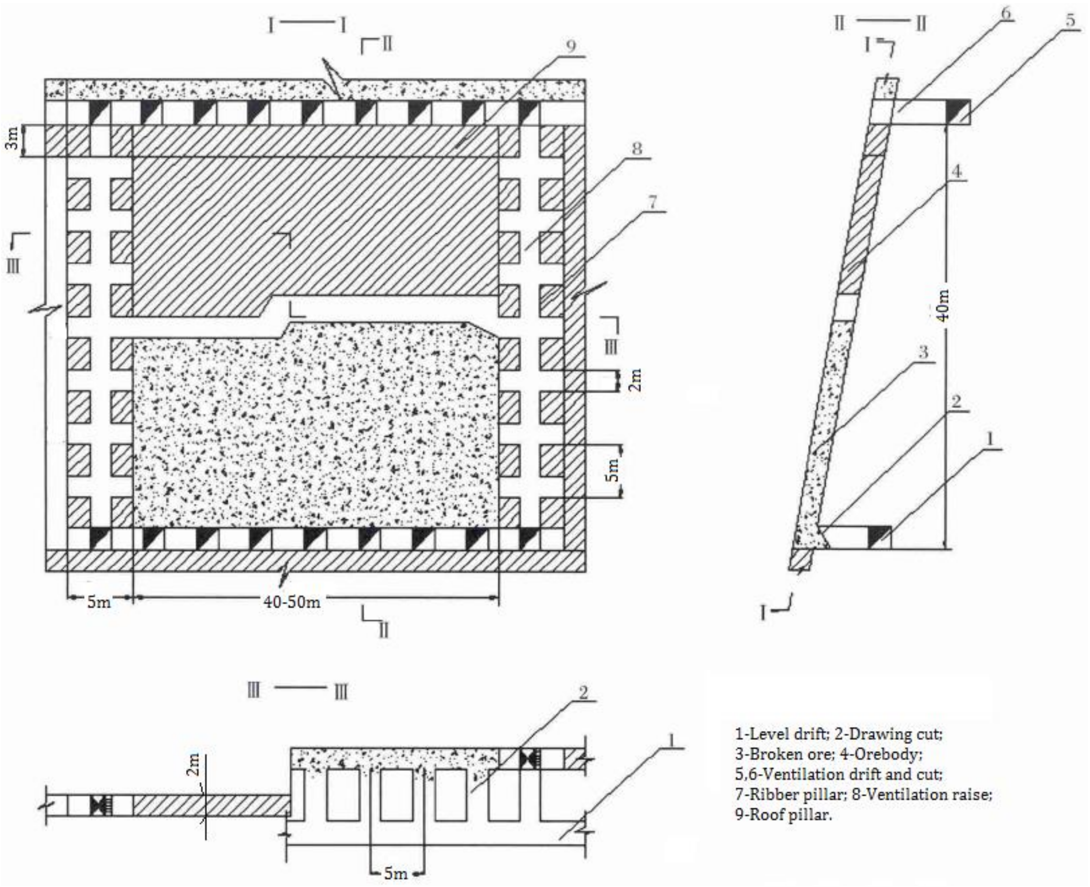

Figure 2 Short-hole shrinkage stoping method used in the upper veins of Bayi gold mine

2 Methodology

In this paper, mining method selection was regarded as a system engineering problem with multi-objective decision-making. A model of mining method optimisation was built up based on the value engineering principle.

2.1 Method of value engineering principle

The method of the value engineering principle is to coordinate the most important aspects of the study object, i.e. to systematically analyse all functions and cost of the object, and to continually innovate resulting in improvement of the management and value of the object (Ismail et al. 2010; Zhang 2009). The purpose of the value engineering principle is to make a product or an object have a suitable value at the lowest cost. Therefore, the relationship between value, function and cost of the value engineering principle is built up in the form of Equation 1:

$$V = \frac{F}{C} \tag{1}$$

where:

V = value.

F = function.

C = cost.

In Equation 1, we can see that there are usually five ways to improve the product value:

- To cut down cost for a fixed function.
- To improve function at a fixed cost.
- To largely improve function at a small increase of cost.
- To improve function meanwhile to cut down cost.
- To largely cut down cost at a small reduction of function.

The features of the value engineering principle method include:

- The main purpose of the value engineering principle is to improve value and reduce the cost, resulting in maximum benefit of the object.
- The focus of the value engineering principle is to analyse the function of product or operation process, and not only to analyse the relationship between function and cost of product or operation process qualitatively, but also to analyse that relationship quantitatively, in order to select suitable ways to achieve the function of the object.
- The value engineering principle method is an activity of management. In application, it is important to effectively organise all aspects of the object to reach the planned target.

2.2 Working procedure of value engineering principle method

Generally, there are four stages divided into 12 steps when applying the value engineering principle method (Table 1).

Table 1 **Working procedure of the value engineering principle method**

Stage	Step	Questions answered
1. Preparation stage	1.1 Object selection 1.2 Staff organisation 1.3 Making a plan	What is the object of value engineering?
2. Analysing stage	2.1 Information collection 2.2 Function analysis 2.3 Function assessment	What is the usage, cost and value of the object?
3. Innovating stage	3.1 Scheme innovation 3.2 Scheme assessment 3.3 Proposal design	Is there any other scheme? What is the cost of the scheme?
4. Implemention stage	4.1 Plan examination 4.2 Implement and check 4.3 Achievement identification	Is the value achievement satisfied?

3 Results and analysis

3.1 Basic data of the rock masses

3.1.1 Strength of the rock specimen

In Bayi gold mine, vein rocks are mainly diorite and quartzite; the proximal enclosing rock of veins is mainly quartz phyllite. Controlled by a set of northwest–southeast shear zones and ruptured by a north or northwest shear fault, those rock bodies are heavily extruded and stretched. Tested in a laboratory, the physical and mechanical properties of the rock specimen are listed in Table 2.

Table 2 Physical and mechanical properties of the rock specimen

Rock type	Dry density (g/cm^3)	Compressive strength (MPa)	Tensile strength (MPa)	Compressive test		Shear test	
				Elastic modulus (GPa)	Poisson's ratio	Inter-friction angle (°)	Cohesion (MPa)
Quartzite	2.60	56.0	1.62	28.7	0.31	40°12′	17.4
Quartz phyllite	2.62	42.7	1.24	29.7	0.38	38°04′	15.6
Diorite	2.61	80.9	2.27	34.1	0.19	42°12′	20.5

3.1.2 Classification of the rock masses

In order to use the CSIR classification system (Bieniawski 1974) to evaluate rock mass quality, a field investigation was done. Hence, the rock mass rating (RMR) is calculated as follows:

$$\mathrm{RMR} = R_1 + R_2 + R_3 + R_4 + R_5 + R_6 \tag{2}$$

where:

R_1 = score of rock strength.

R_2 = score of rock quality designation (RQD).

R_3 = score of joint spacing.

R_4 = score of joint condition.

R_5 = score of underground water condition.

R_6 = score of modified value based on joint direction.

The resulted RMRs of the three types of rock masses are listed in Table 3.

Table 3 Resulted RMRs of rock masses in Bayi gold mine

Index	**Quartzite**		**Quartz phyllite**		**Diorite**	
	Data	**Score**	**Data**	**Score**	**Data**	**Score**
R1	56.0 MPa	7	42.7 MPa	6	80.9 MPa	7
R2	48.7%	8	48.5%	8	56.4%	12
R3	12.5 cm	8	10.7 cm	8	13.0 cm	8
R4	Joint plane is rough and weak, with width < 1 mm	20	Joint plane is rough and weak, with width < 1 mm	20	Joint plane is rough and hard, with width < 1 mm	25
R5	Wet	10	Wet	10	Wet	10
R6	Unfavourable	-10	Unfavourable	-10	Unfavourable	-10
RMR	–	43	–	42	–	52

Therefore, according to the CSIR system (Table 4), classification of rock masses of the gold mine are of the third class, i.e. a fair quality of rock masses.

Table 4 CSIR classification of rock mass based on RMR score

RMR score	**100–81**	**80–61**	**60–41**	**40–21**	**< 20**
Class	1st	2nd	3rd	4th	5th
Rock quality	Very good	Good	Fair	Poor	Very poor
Average stable time	(span 15 m) 20 years	(span 10 m) 1 year	(span 5 m) 7 days	(span 2.5 m) 10 hrs	(span 1 m) 30 min
Cohesion (kPa)	> 400	300–400	200–300	100–200	< 100
Inter-friction angle (°)	> 45	35–45	25–35	15–25	< 15

3.2 Mining method optimisation

3.2.1 Primary selection of mining method

Based on the geological and mining conditions of the lower thick orebody in Bayi gold mine, the primary selected mining methods include cut-and-fill stoping method, sublevel stoping method with delayed backfill, and level open stoping method with delayed backfill. Similar to level open stoping with delayed backfill, vertical crater retreat (VCR) stoping with delayed backfill could also be used; however, as the dipping angle of the lower thick orebody is only about 58° and the ore grade is comparatively high, if the VCR method was used, ore dilution or ore losses would be considerably high. Hence, the VCR method with delayed backfill is not taken into consideration.

3.2.2 Selected functional parameters of mining methods

For mining method optimisation, a comprehensive multi-objective decision-making index system is needed. To use the method of value engineering principle to optimise the mining method, some functional parameters of mining methods should be selected (Xu 2011). Actually, those multi-objectives of mining method optimisation are the functional parameters and the cost of mining with backfilling. Therefore, for those three primary selected mining methods, six functional parameters are selected:

1. Safety and working conditions.
2. Stope production capacity.
3. Miners' productivity.
4. Stope preparation workings.
5. Ore losses.
6. Ore dilution.

3.2.3 Assignment of selected functional parameters

The aforementioned six functional parameters should be assigned. For the parameter of safety and working conditions, which is a qualitative parameter mainly including stope stability, stope support, stope ventilation, dust control, working safety measures, etc, an expert grading method was used. Hence, the safety and working conditions are divided into five types, i.e. poor, rather poor, fair, rather good and good. Each type has a value of 1, 3, 5, 7 or 9 respectively. Six experts were invited to evaluate these parameters of those three primary selected mining methods, and the average grading data are listed in Table 5.

For the other five functional parameters, which are quantitative parameters, an engineering analogy method was used. Therefore, for each primary selected mining method, the mining conditions of Bayi gold mine are compared with 10 other similar gold, nickel or copper mines which are in production. The average data of each group of the 10 mines of those five functional parameters are listed in Table 5. Besides, the cost of mining and backfill is also listed in Table 5 (Wang 2012; Yu 2009).

Table 5 Assignment of parameters of primary selected mining methods

Parameter type	Parameter	Unit	Average data		
			Cut-and-fill stoping	Sublevel stoping with delayed backfill	Level open stoping with delayed backfill
Functional parameters	a) Safety and working conditions	Score	7	7	5
	b) Stope product capacity	t/d	184.1	272.7	733.0
	c) Miners' productivity	t/shift	11.4	49.3	62.0
	d) Stope preparation workings	m/10^3t	15.1	9.0	8.1
	e) Ore losses	%	6.4	12.6	17.1
	f) Ore dilution	%	8.4	5.2	8.6
Cost parameter	Cost of mining and backfill	Yuan/t	38.3	52.8	66.5

3.2.4 *Determination of importance degree of functional parameters*

For the six functional parameters, their importance degree should be different. To evaluate the comparative importance of each functional parameter, a 0–1 compulsory scoring method was used. The six experts were also invited to make their judgements; comparing the safety and working conditions with the other five functional parameters one by one, the more important one obtains a score of 1 and the less important one obtains a score of 0. There should be no equal importance in comparison of two parameters, i.e. there must be one parameter obtaining 1 and the other obtaining 0. For instance, the judgement of No. 1 expert is listed in Table 6, in which the most important functional parameter has the highest score, and the total score of each functional parameter should not be 0.

Table 6 0-1 compulsory scoring sheet (No. 1 expert)

Parameter	a	b	c	d	e	f	Total score
a	*	1	1	1	1	1	5
b	0	*	1	0	0	0	1
c	0	0	*	1	0	0	1
d	0	1	0	*	0	0	1
e	0	1	1	1	*	1	4
f	0	1	1	1	1	*	4

Note: the parameters are shown in Table 5.

Finally, a judgement summary of the six experts could be given out, as shown in Table 7, in which the most important parameter has the highest average score. It can be seen that the importance sequence of the six function parameters is a, e, f, c, b, d.

Table 7 Summary of importance judgement of functional parameters

Parameter	Judgement by experts						Total score	Average score
	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6		
a	5	5	5	5	5	5	30	5.00
b	1	2	1	1	2	1	8	1.33
c	1	1	2	2	2	2	10	1.67
d	1	1	1	2	1	1	7	1.17
e	4	4	4	3	3	4	22	3.67
f	4	3	3	3	3	3	19	3.17

3.2.5 *Score calculation of functional parameters of the three primary selected mining methods*

Based on the average score of functional parameters listed in Table 7, taking any one of the three primary selected mining methods as a benchmark, for example, taking the cut-and-fill stoping method as the benchmark, scores of functional parameters of the other two mining methods are calculated. During calculation, it could be found that among those six functional parameters, three of them, i.e. a, b and c, whose score should be the larger the better (proportional relation); and the other three parameters, whose score should be the smaller the better (inverse relation), hence, we have:

$$F_{mij} = \frac{M_i}{M_{ij}} \times Z_j \quad \text{or} \quad F'_{mij} = \frac{M_{ij}}{M_i} \times \overline{Z}_j \tag{3}$$

where:

M_i = parameter value of the mining method being calculated, which is listed in Table 5.

M_{ij} = parameter value of the benchmark mining method, which is also listed in Table 5.

Z_j , $\overline{Z}_j$ = average score of functional parameter of the benchmark mining method, which is listed in Table 7.

F_{mij} , F'_{mij} = calculated score of functional parameter for proportional relation and inverse relation respectively.

The calculated scores of functional parameters of those three primary selected mining methods are listed in Table 8.

Table 8 Score of functional parameters of primary selected mining methods

Parameter	Cut-and-fill stoping	Sublevel open stoping with delayed backfill	Level open stoping with delayed backfill
a	5.00	5.00	3.57
b	1.33	1.97	5.30
c	1.67	7.22	9.08
d	1.17	1.96	2.18
e	3.67	1.86	1.37
f	3.17	5.12	3.10
Total score	16.01	23.13	24.60

3.2.6 Value coefficient of three primary selected mining methods

Based on Equation 1, for mining method optimisation, the value coefficient is calculated as follows:

$$V_i = \frac{F_i}{C_i} \tag{4}$$

where:

V_i = value coefficient of a mining method, t/yuan, the physical meaning of which is the function for mined ore tonnages over unit cost.

F_i = total score of functional parameters of a mining method.

C_i = cost of mining and backfilling of the selected mining method, yuan/t.

The calculated value coefficients of the primary selected mining methods are listed in Table 9.

Table 9 Calculated value coefficient of primary selected mining methods

Mining method	Cut-and-fill stoping method	Sublevel open stoping with delayed backfill	Level open stoping with delayed backfill
Function score	16.01	23.13	24.60
Cost of mining and backfilling (yuan/t)	38.30	52.80	66.50

Value coefficient (t/yuan)	0.42	0.44	0.37

From Table 9, it could be seen that the sublevel open stoping method with delayed backfill has the largest value coefficient. Hence, the optimised mining method is sublevel open stoping with delayed backfill.

3.3 Design of the sublevel open stoping method with delayed backfill

Considering the general quality of rock masses in Bayi gold mine, a standard stope of sublevel open stoping method with delayed backfill was designed, as shown in Figure 3 (Tian & Cai 2012).

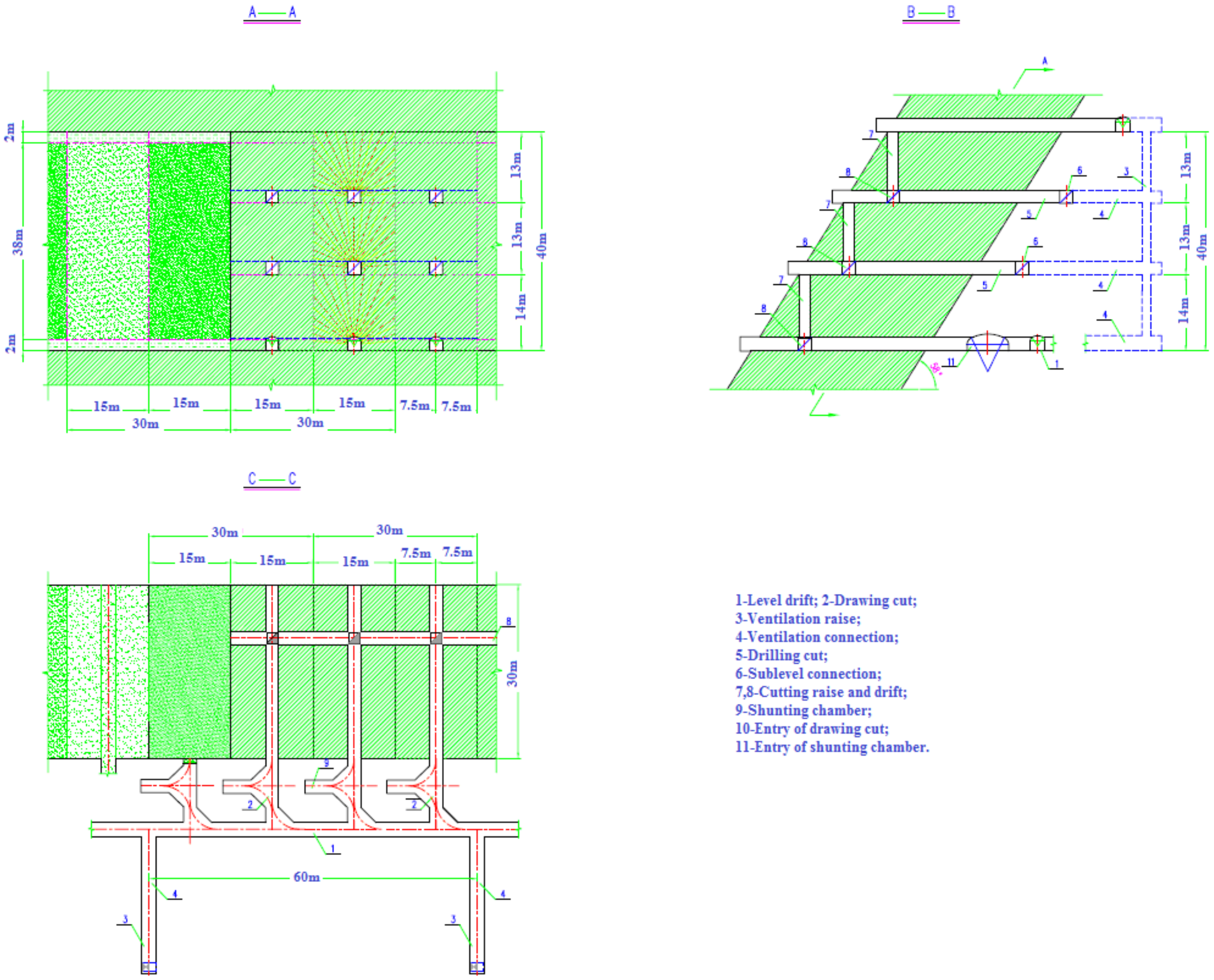

Figure 3 Designed stope of sublevel open stoping method with delayed backfill of the mine

The main technical–economic data of the designed stope of sublevel open stoping method with delayed backfill for the gold mine are listed in Table 10. It should be noted that the orebody thickness of a designed standard stope is 30 m, and if the orebody thickness is up to 60 m, some technical–economic data listed in Table 10 should be better.

Table 10 Main technical–economic data of the designed standard stope

No.	Index	Unit	Data
1	Stope size	–	–
1–1	Length	m	60
1–2	Thickness	m	30
1–3	Height	m	40
1–4	Sublevel height	m	13–14
2	Stope production capacity	t/d	335
3	Miners' productivity	t/shift	55.8
4	Stope preparation workings	m/10^3t	6.75
5	Ore losses	%	14.38
6	Ore dilution	%	10.0
7	Cost of mining and backfilling	Yuan/t	55.0

4 Conclusion

In order to find out a suitable mining method for the lower thick orebody in Bayi gold mine, six functional parameters, i.e. safety and working conditions, stope production capacity, miners' productivity, stope preparation workings, ore losses and ore dilution, and one cost parameter are taken into consideration, and an optimisation model based on the value engineering principle method has been set up. The optimised mining method, i.e. sublevel open stoping method with delayed backfill, was selected based on the analysis and calculation results. The sublevel open stoping method with delayed backfill was designed, and the main technical–economic data of a designed standard stope were calculated. It is believed that the optimised mining method should meet the requirements of mining production and mine safety. Therefore, the designed mining method has been put into stope preparation work of the lower thick orebody in the mine.

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