Provision of a Mathematical Model for Economic Comparison of Production Drilling Methods in Sublevel Stoping

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Sublevel stoping is an underground mining method which has a low level of production cost. As well main part of the production cost is related to choosing of the drilling method in each stope. The main objective of this paper is to generate a model for identification of the best drilling choice in each case. In order to developing a mathematical model, 150 stopes has been designed by hypothesized dimensions and drilling patterns. In each case production cost was calculated based on extracted ore unite. The out puts come from through calculation of the hypothesized designing on account of different thicknesses of the ore body and heights of the production blocks. A mathematical model has been developed through non-linear regression technique on the basis of the out puts. The generated model is able to define dissimilar production cost per extracted ore unit based on each production drilling method. Therefore the best choice is the drilling method which has the lowest rate of dissimilar production cost. Verification of the model has been carried out on some random data. Accordingly the result of verification has been acceptable by reason of a suitable adaptation ratio.

Keywords: Sublevel Stoping, Production Drilling, Economic Comparison, Mathematical Modeling

1. Introduction

Sublevel stoping is an underground mining method which can be applied for extraction of metalliferous orebodies by low cost rate. This method has several constraints for applying on account of the characteristics of an ore body. If these limitations allow to designers for applying sublevel stoping, production drilling method plays an important role to define the extraction cost rate [1]. Several production drilling methods are applied in sublevel stoping. The variety of these methods effect directly on extraction cost rate. Therefore choosing the suitable production drilling is one of the main decision making events for designing of each stope [1]. Thus, development of an economical comparison model, for identifying the best choice of production drilling containing the lowest cost rate, is excessively fruitful to design of a stope.

In this paper the procedure for creation of an economical comparison model is described on the basis of dissimilar cost rate per volume unite of in-situ ore. Since several parts of a stope is independent of the type of the chosen production drilling method, for that reason the related costs is similar amongst different production drilling methods. Therefore the procedure just considers dependent parts of a stope in the model. Dissimilar cost which is generated through applying different drilling methods, is the main cause to compare the production drilling methods economically.

The objective of the paper is presenting a model for primary assessing of the achievable production drilling methods in sublevel stoping. The model which is developed on the basis of the characteristics of the orebody, guides the designers to select the most economical choice of drilling method in each stope.

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2. Summary of Sublevel Stoping Method

Sublevel stoping is recognized as blasthole or longhole stoping method. This underground mining method is an open stoping, high production, bulk mining, applicable to large, steeply dipping, regular ore bodies having competent ore and rock that requires little or no support. Production ranges from 15 to 40 tons per employee shift, and individual stopes may produces in excess of 25,000 tons per month [2]. In recent decades sublevel stoping accounts for some 9% of US and 3% of the world noncoal production [3].

The typical ore body required for successful sublevel stoping must be strong to fairly strong and self supporting. The dip of the ore body footwall must be such that it exceeds the angle of repose of the broken ore, which permits gravity flow of blasted ore through to drowpoints and chutes. Ore bodies are typically a minimum of 6 m wide to afford efficient application of longhole blasting [2].

In figure 1 an isometric view of an open stope sublevel stoping operation is illustrated. In this figure several divisions of operational activities of an individual open stope is demonstrated in detail (‘See figure 1’).

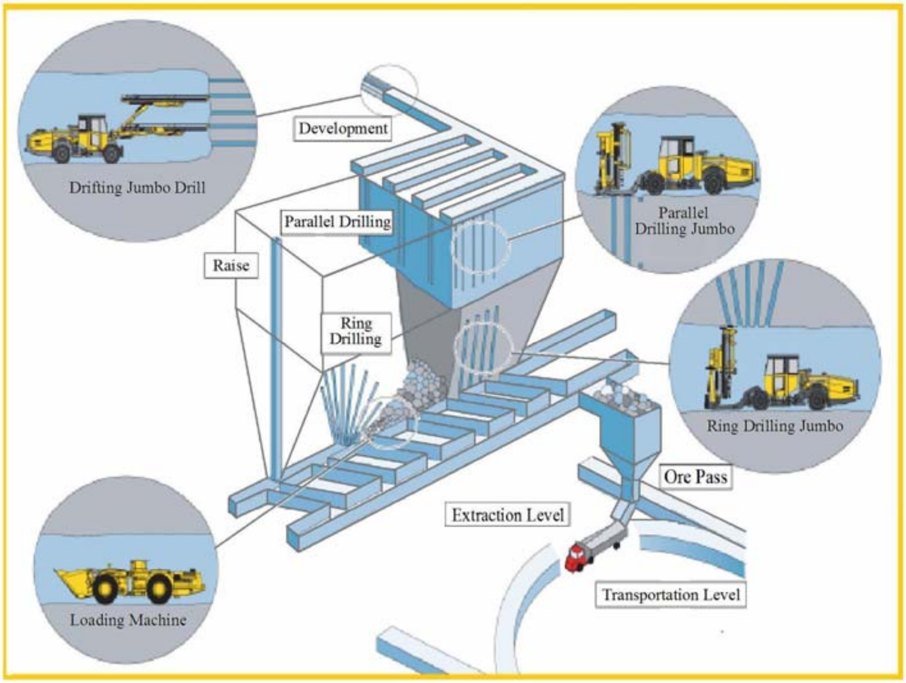

Figure1. Isometric view of an open stope sublevel stoping operation [4]

Production drilling is accomplished using longhole equipment. Innovation in production drilling equipment has improved the efficiency and expanded the applications of sublevel stoping more than any other factor. Since the early 1970s the ‘column and arm’ longhole drilling method, commonly using 50 to 75 mm diameter holes, has largely been replaced by mechanized longhole drilling [5]. Standard percussion longhole drills are still being used on mobile carriers, but the most efficient methods employ ‘high pressure’ pneumatic ‘down the hole’ (DTH) drills, and ‘electric hydraulic’ rotary and ‘rotary percussion’ equipment, capable of drilling a range of hole sizes up to 200 mm. Holes can commonly be drilled to depths of 90 m with less than 2% deviation with DTH equipment [5]. Best stope drilling and blasting efficiency result when a pattern of vertical, parallel holes can be designed.

Production activities of sublevel stoping method is consisted of production drilling, charging and blasting and then just loading of blasted ore in draw points. But the most effective factor on production rate amongst different items of the operation is the type of drilling system. As above, Ring and parallel productive drilling are the successful methods among conventional and modern drilling methods of sublevel stoping. These two methods have high level performance and productivity ratio.

Figure 2 shows a schematic illustration of ring drilling pattern in an open stope ('see figure 2.A'). In this style of production drilling, blast holes are drilled on a ring pattern in ore body from the endpoint of each production sublevel drift to around the drift in a radial form. Mechanized hydraulic Ring drilling jumbo is the most fitting drilling equipment in this regard. Common diameter of blast holes in ring drilling system are between 48 – 64 mm with lengths up to 25 m. The drilling rigs used are of special design with extension drill steels. The separation between drilled sections is usually around 1.2 and 1.8 m [6]. The collaring, orientation and deviation of the blast holes are some of the operative conditions necessary to obtain good blasting results. This means that it is necessary to use special orientation systems and accessories, and not drill blastholes of more than 25 m [6].

Longholes do not generally exceed 25 m because hole deviation and manage turn into big problems [5]. The performance of the drilling system in this respect is between 120 – 180 m in a shift. Also the production range of drilling and blasting in this case would be between 1.5 – 2.5 cubic meters ore per drilled meter [5]. In each blast 3 or 4 rows are blasted generally. Blast hole spacing is not the same in collars and ends, but burden is regularly uniform.

Parallel drilling system is the modern production drilling pattern of sublevel stoping which is fulfilled by high pressure DTH jumbos. In this case blastholes are drilled in bottom of the production drifts downward to draw points. Enlargement of the endpoint of each production drift is the first stage to implement Parallel drilling method. Then the sides of each production drift are excavated in width up to thickness of the ore body. Blastholes diameter in parallel drilling is between 105 – 200 mm with lengths up to 90 m. The performance of the drilling system in this respect is about 50 m per shift. As well ore production rate of drilling and blasting is related to hole lengths, between 8-18 m^3/m [5] ('see fig 2. B').

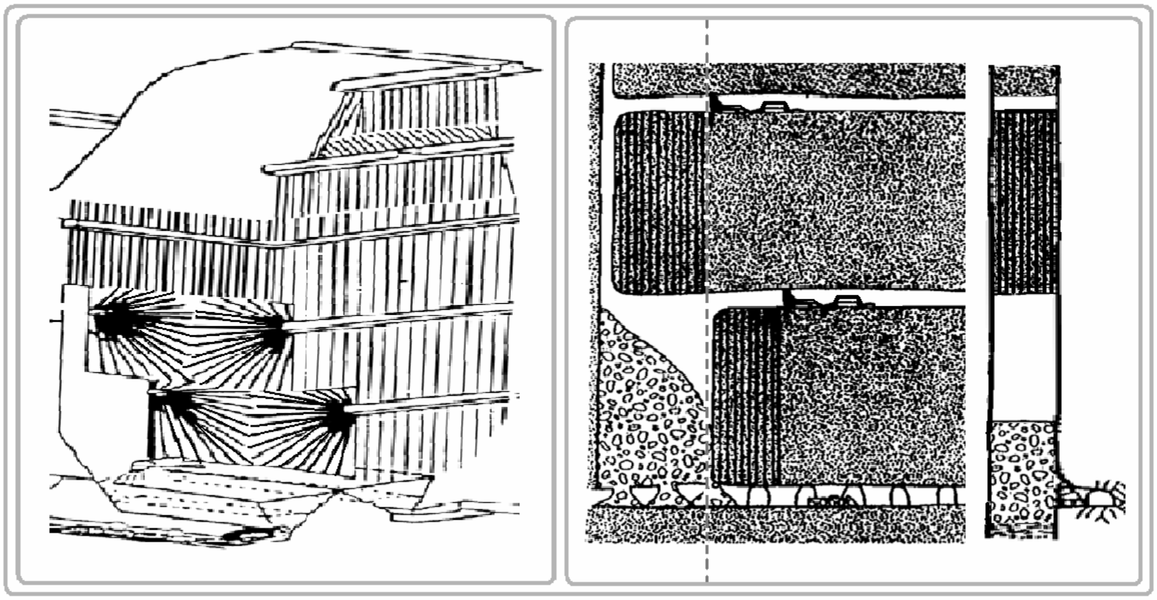

Fig 2. Schematic illustration of A.(left): Ring drilling, B.(right): Parallel drilling

3. Modeling Procedure

The procedure is developed on the basis of the variety of dissimilar costs amongst applications of different production drilling systems. Whereas ring and parallel drilling systems are the most effective drilling methods in sublevel stoping in productivity and mechanize ability views, in this paper economic consideration has been performed on just two systems. Therefore in order to achieve this objective, a range of typical conditions of a hypothesized stope is assumed. Then through designing of each stope and calculation of the costs, economic comparison is carried out.

3.1. Economical comparison criteria

Whereas most costs of the execution of sublevel stoping in different stopes are similar, such as; opening of mine, development of accesses and main haulage levels, development of stopes, loading in draw points and hauling in transportation levels, these costs are not effective on economic considerations among different designations. Thus dissimilar costs such as; production sublevel drifts' development, production drilling and amount of explosives, have been just considered concerning economic comparison consideration in this paper.

Regarding economic comparison on the basis of the dissimilar costs of implementation of sublevel stoping designations, three category of cost would be considered as bellow:

- Production sublevel drifts development cost
- Production drilling cost
- Consumable explosives cost

consequently caused by calculation of the total dissimilar cost of each drilling method, the total cost of a production block on the basis of both ring and parallel drilling would be calculate according to 'equation (1)': $P = C / V$ (1)

In 'equation (1)' where P is the total dissimilar production costs per in situ ore volume unit, C is the total dissimilar production costs of a production block and V is the total volume of in situ ore in a production block. Further to description of the above mentioned criteria, three indexes are described as economic comparison indexes between ring and parallel drilling systems in each production block as follow:

- Production block dimensions
- Drilling and blasting pattern
- Total Dissimilar costs

3.2. Developing of the model

Respecting consideration of economic comparison basis of dissimilar costs, production block dimensions would be assumed as table 1 explanation ('see table 1').

Table1. Production block dimensions explanation

Block dimensions	*Description*	*Typical range (m)*
Length	Horizontal distance between slot raise and access raise align length of the stop	90
Width	Horizontal distance between boundaries of hanging wall and footwall	10 – 40
Height	Vertical distance between bottom of crown pillar and stop undercut	30 – 90

Drilling and blasting pattern would be designed on the basis of a typical pattern [7]. The explanation of the pattern is described in table 2 and table 3 regarding ring and parallel drilling systems (‘see table 2-3’). In all tables For the sake of brevity the abbreviation Ring drilling J. indicates Ring drilling jumbo and HP DTH J. indicates of high pressure DTH Jumbo, P indicates Parallel drilling, R_1 indicates Ring drilling with one production sublevel drift, R_2 indicates Ring drilling with two production sublevel drift, R_3 indicates Ring drilling with three production sublevel drift.

Table2. Typical drilling / blasting pattern design for ring drilling

Parameter	*Description*	*Unit*
Hole diameter	51	mm
Drilling rig type	Ring drilling Jumbo	–
Production drift cross section	3×3	m
Vertical distance between sublevels	12	m
Horizontal distance between production drifts	Min 6	m
Hole length	Max 24	m
Spacing in front holes	Min:0.1, often:0.5	m
Spacing in end holes	Max 2.5	m
Burden	1.5	m
Hole dip	Max 10 along stope slot	degree
ANFO consumption	1.9	Kg/m(hole)
Primer consumption	0.14	Cartridge/m(hole)
Cordtex consumption	1.5	m/m(hole)

Table3: Typical drilling and blasting pattern design for parallel drilling

Parameter	*Description*	*Unit*
Hole diameter	152	mm
Drilling rig type	HP DTH J.	–
Number of production drifts per stope	1	–
Height of production drifts	4	m
Width of production drifts	Stope width	m
Hole length	Max 120	m
Spacing	4	m
Burden	3.7	m
Distance between last hole and hanging wall/footwall	1.4	m
Number of additional holes in slot	2	–
ANFO consumption	13.88	Kg/m(hole)
Primer consumption	12	Cartridge/m(hole)
Cordtex consumption	2.5	m/m(hole)

The principle of cost calculation is assumed basis of a typical model [7] according table 4 (‘see table 4’).

Table4. Costs determination, based on SME values in $US

Parameter	*Description*	*Unit*
Production drift development, 3×3 m	12.75	$\$/m^3$
Production drift development, 4 m height	12.3	$\$/m^3$
Drilling, 51 mm diameter, ring	2.95	$/m
Drilling, 152 mm diameter, parallel	8.2	$/m
ANFO	265	$/ton
Primer	1.25	$/cartridge
Cordtex	1.64	$/m

The ore body geometry parameters as regards consideration of economic comparison on the basis of the execution of high performance ring and drilling systems is assumed as follow [8]:

- Thickness of ore body: 10 to 40 m
- Dip of ore body (dip of the biggest alignment of the ore body) : 90°

Height of the production block in order to economic comparison consideration is assumed vertical distance between crown pillar and sill pillar, 35 to 90 m [8].

For developing the economical 147 stopes was designed based on different hypothesized dimensions of a stope. As a sample in figure 3 the pattern of ring drilling respecting thickness: 35 m, height: 90 m in a vertical cross section view has been illustrated ('see figure 3'). In this hypothesized stope due to large thickness of assumed ore body it is possible to excavate 1, 2 or 3 production drifts in each sublevel.

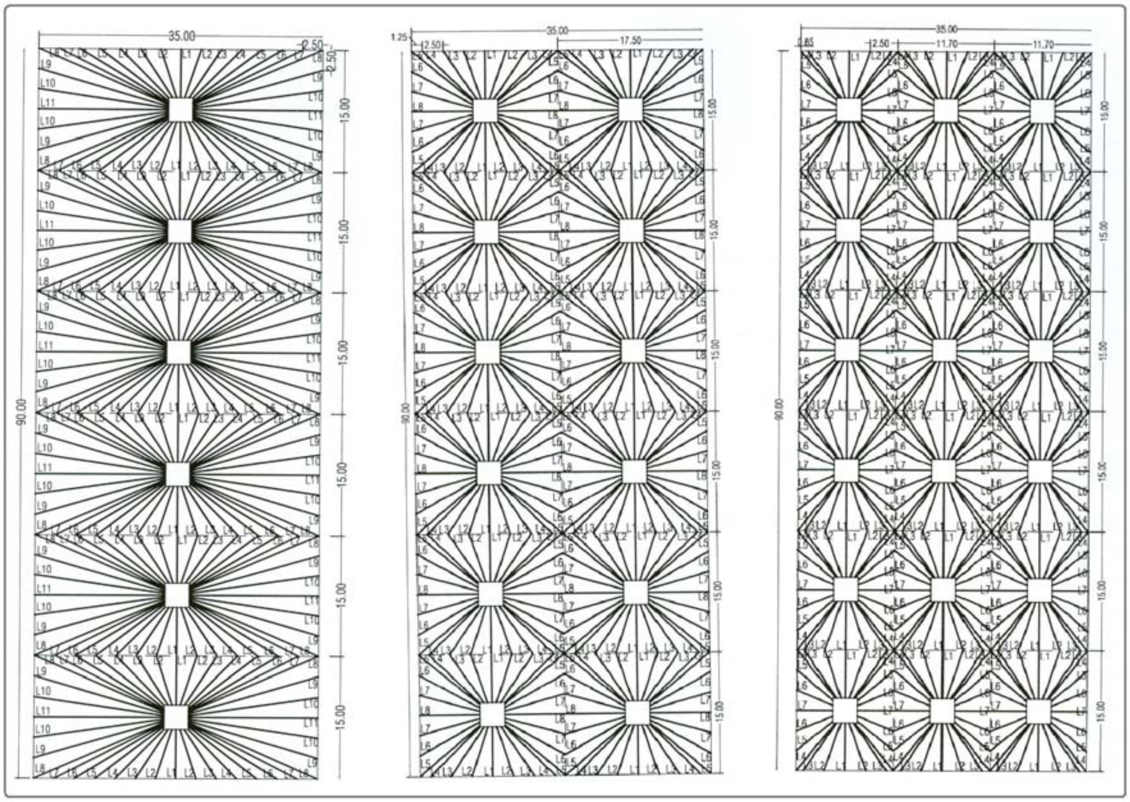

Fig 3. A.(left): Ring drilling pattern (vertical cross section) in Thickness 35 m and height 90 m including 1 production sublevel drift, B.(middle): Ring drilling pattern including 2 production sublevel drifts, C.(left): Ring drilling including 3 production drift in each sublevel

In figure 4 parallel drilling pattern (horizontal longitudinal section) with respect to Thickness 35 m, height 90 m and Length of stope 90 m as a sample is illustrated ('see figure 4').

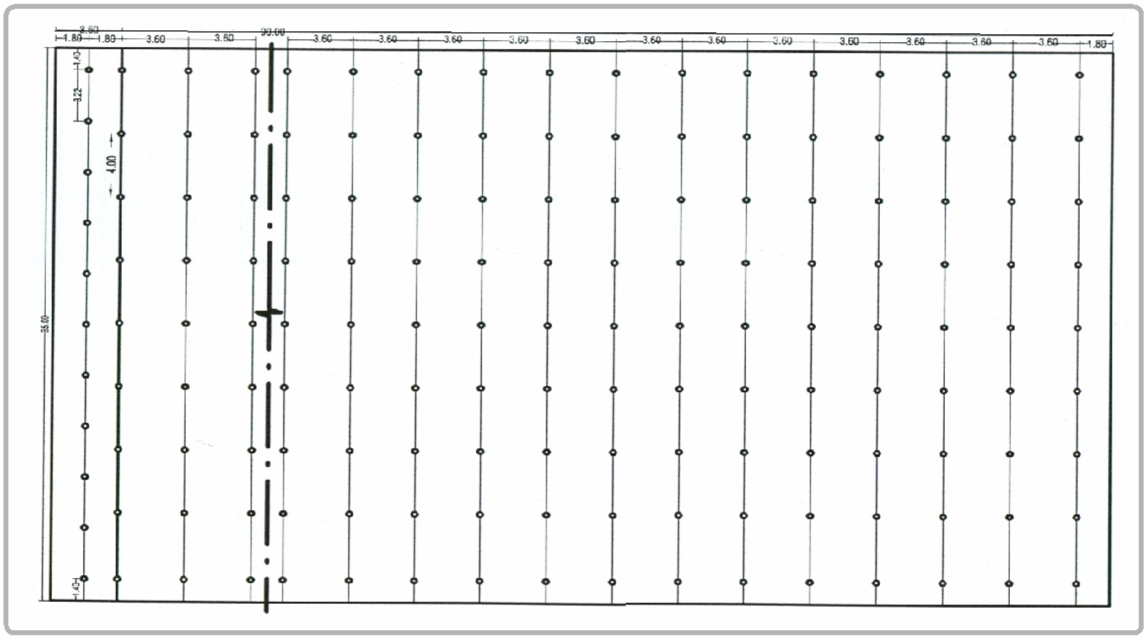

Fig 4. Al, B.(right): parallel drilling (horizontal longitudinal section), Thickness 35m and length of stope 90 m

In the next stage of procedure results of the designations in each assumed thickness of ore body and height of production block, totally including 49 geometrical conditions, is collected. According to table 5 the amount of dissimilar cost of viable drilling system due to $US/m^3 of in situ ore is presented ('see table 5').

Table5. Results of designing with different ore body and production block's condition

No.	*Height (m)*	*Thickness (m)*	*Dissimilar cost ($US/m^3)*			
			R_1	R_2	R_3	P
1	30	10	3.7	–	–	2.9
2	40	10	3.7	–	–	2.5
3	50	10	3.9	–	–	2.3
4	60	10	3.7	–	–	2.1
5	70	10	3.7	–	–	2
6	80	10	3.8	–	–	1.9
7	90	10	3.7	–	–	1.9
8	30	15	3.5	–	–	2.7
9	40	15	3.6	–	–	2.3
10	50	15	3.8	–	–	2.1
11	60	15	3.5	–	–	2
12	70	15	3.6	–	–	1.9
13	80	15	3.7	–	–	1.8
14	90	15	3.5	–	–	1.7
15	30	20	3.6	3.7	–	2.8
16	40	20	3.6	3.7	–	2.5
17	50	20	3.7	3.9	–	2.2
18	60	20	3.6	3.7	–	2.1
19	70	20	3.6	3.7	–	2
20	80	20	3.6	3.8	–	1.9
21	90	20	3.6	3.7	–	1.8
22	30	25	3.7	3.9	–	2.8

No.	*Height (m)*	*Thickness (m)*	*Dissimilar cost (\$US/m^3)*			
			R_1	R_2	R_3	P
23	40	25	3.8	4	–	2.4
24	50	25	3.9	4.1	–	2.2
25	60	25	3.7	3.9	–	2
26	70	25	3.7	3.9	–	1.9
27	80	25	3.8	4	–	1.82
28	90	25	3.7	3.9	–	1.8
29	30	30	3.8	3.5	–	2.7
30	40	30	4	3.6	–	2.3
31	50	30	4.1	3.8	–	2.1
32	60	30	3.8	3.5	–	1.9
33	70	30	3.9	3.6	–	1.8
34	80	30	4	3.7	–	1.8
35	90	30	3.8	3.5	–	1.7
36	30	35	4	3.8	4.09	2.7
37	40	35	4.2	3.9	4.13	2.3
38	50	35	4.3	4	4.29	2.1
39	60	35	4	3.8	4.09	1.9
40	70	35	4.1	3.9	4.11	1.8
41	80	35	4.2	4	4.22	1.72
42	90	35	4	3.8	4.09	1.7
43	30	40	4.2	3.6	3.78	2.7
44	40	40	4.4	3.6	3.84	2.4
45	50	40	4.5	3.7	3.98	2.14
46	60	40	4.2	3.6	3.78	2
47	70	40	4.3	3.6	3.8	1.9
48	80	40	4.4	3.7	3.91	1.8
49	90	40	4.2	3.6	3.78	1.7

3.3. Mathematical Modeling

In order to generate an economical model for identification of best drilling choice, the below procedure was applied. This procedure was extracted from the applied economical comparison method and its final results. Height of stope and thickness of ore body are two variables in the model. The objective outcome from the model is dissimilar cost per volume unit of the in-situ ore for each drilling choice. Thus on the basis of the data from economical comparisons between drilling choice in each specific condition of height and thickness, statistical analysis is achieved. Therefore through regression technique required mathematical function is produced. The best fitting on the experimental data was created from nonlinear multiple regression curves. Distribution of the data is an effective item to fit the best regression curve. Accordingly for each equation, an Index of determination (r^2) is concluded which identifies fitting ratio of each curve. Index of determination (r^2) varies between; 0 to 1. The closest Index to 1 shows the best fitting of the regression curve on actual data distribution.

In this research regression was performed through statistical software. Between the concluded curves, the best fitting of each condition has been demonstrated in table 6 (“See Table 6”). In this table where C_{R1}; cost of ring drilling with one production drift in each sublevel, C_{R2}; cost of ring drilling with two production drifts in each sublevel, C_{R3}; cost of ring drilling with three production drifts in each sublevel, C_P; cost of parallel drilling, r^2; Index of Determination, H; height of production block, T; thickness of ore body.

Table 6. Mathematical model for identification of dissimilar cost for drilling choice in different condition of thickness of ore body and height of production block

No.	*Thickness range (m)*	*Regression Equation*	*r^2*
1	10 - 40	$C_{R1} = 4.0659183 - (3.877\times10^{-4})\,H - (4.65884\times10^{-2})\,T + (1.37483\times10^{-3})\,T^2$	0.87
2	20 - 40	$C_{R2} = 3.251142 - (2.142\times10^{-4})\,H + (4.59143\times10^{-2})\,T - (8.857\times10^{-4})\,T^2$	0.13
3	35 - 40	$C_{R3} = 5.15333 - (7.1429\times10^{-5})\,H - (8.1904\times10^{-4})\,T^2$	0.82
4	10 - 40	$C_P = 3.171173 - (1.57551\times10^{-2})\,H - (4.561\times10^{-3})\,T$	0.88

In order to estimate dissimilar production cost of each drilling method for choosing the best drilling choice, the model primarily is suitable for economical calculation. The calculation is executed based on each specific thickness of ore body and height of production block. Therefore by the model dissimilar cost amount of drilling alternatives is calculated for feasibility studies.

3.4. Verification of mathematical model

For verification of the mathematical model some random data include different thicknesses of ore body and heights of production block were selected. Consequently the amounts of dissimilar cost of production were extracted from the results table. Also the same costs were calculated through mathematical model. Then the actual data and estimated date were compared and adaptation ratio was calculated. According to table 7 adaptation ratio is between 96.64 to 100.20 percent ("See table 7").

Table7. Verification of the mathematical model based on some random data consist of different thicknesses of ore body and heights of production block

No.	*Thickness (m)*	*Height (m)*	*Model*	*r^2*	*Cost from model (\$/m^3)*	*Cost from design (\$/m^3)*	*Adaptation ratio (%)*
1	10	30	C_{R1}	0.87	3.726	3.71	100.43
2	25	70	C_{R1}	0.87	3.733	3.74	99.81
3	20	80	C_{R2}	0.13	3.798	3.84	98.91
4	35	60	C_{R2}	0.13	3.760	3.82	98.43
5	40	40	C_{R3}	0.82	3.839	3.84	99.97
6	35	50	C_{R3}	0.82	4.146	4.29	96.64
7	10	40	C_P	0.88	2.495	2.49	100.20
8	40	40	C_P	0.88	2.358	2.36	99.94

4. Conclusion

According to reached results it was proved that method of production drilling is effective on sublevels development, drilling rate and explosive consumption costs. thus as to existing high performance production rate of ring and parallel drilling systems against to other conventional drilling system of sublevel stoping, economical comparison is included just mentioned drilling systems. Concerning ring drilling system, optimum length of blast holes and number of production sublevel drifts are the most sensitive parameters relating to cost effectiveness. Finally main results respecting economical comparison of drilling systems of sublevel stoping are as follow:

In full range of an ore body thickness, using parallel drilling is more economical and cost effectiveness. If applying parallel drilling would be impractical due to technical reasons, ring drilling could be second ideal choice. Ring drilling pattern consist of one production drift in each sublevel, is the most cost effective designation in an ore body up to 30 m thickness. In case of an ore body with thickness over 30 m apply ring drilling pattern include two production drifts in each sublevel is the best designation. With the purpose of apply parallel drilling; generally dissimilar production costs are decreased about 45 percent against execute of ring drilling.

The developed mathematical model identifies dissimilar production cost of each drilling alternatives. Therefore on the basis of thickness of ore body and height of production block economical calculation for feasibility study would be viable step.

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