Economic Comparison of Drilling Systems in Sublevel Stoping Method

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Drilling constitutes an important part of the production process in sublevel stoping method and up to 50% of the total costs can be attributed to this element. With the advent of recently developed sophisticated and expensive drilling machines, sublevel stoping has gained renewed advantage over other similar methods. The use of these machines, however, substantially increases the capital cost of the whole operation and hence choosing the optimum drilling system can produce significant savings in costs. In this paper, drilling patterns have been designed for various conditions of the physical characteristics and geometrical conditions of an ore body. Total costs of some 150 different patterns have been compiled. Based on these empirical data, a practical model has been devised that determines drilling costs in all different feasible situations in sublevel stoping. The model shows that parallel drilling is the most efficient alternative in all workable conditions. As well the break-even orebody thickness in ring drilling between one or two production drifts in sublevels is, in most cases, about 30 meters. The prescribed drilling methods in different circumstances and the model introduced, can serve as useful tools to the mining design engineer in choosing the most economical drilling system when designing a stope.

Keywords: Sublevel stoping, ring drilling, parallel drilling, DTH drilling machines, drilling and blasting pattern, stope height

1. Introduction

It is obvious that, ore extraction with the lowest cost rate is basically the most important point in mining decision making and production planning. Also in sublevel stoping method, which is one of the most useful hard-rock underground mining methods, it is possible to execute several production drilling systems depend on ore body's geometry and production planning with a wide range of different production costs. Therefore applying sublevel stoping method economically should be considered to compare viable production drilling as a fundamental requirement to select the best solution. In this paper with respect to the mentioned idea, firstly sublevel stoping method is described in brief, followed by economic comparison of different drilling systems. In the next stage the criteria of drilling systems of economic comparison is discussed. Consequently the procedure of economic comparison of drilling system in sublevel stoping method analyzed with respect to a wide range hypothesize production block designs, in different geometrical

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conditions of the ore body. As a final point, by studding of dissimilar production costs, we could decide about selecting the most doable system.

2. Sublevel stoping method in brief

Sublevel stoping is one of the most useful underground mining methods in steeply dipping hard-rock ore bodies. Herein mining method existence of a high plunge length in the ore body is essential. It provides required geometrical form to create gravitational ore flow from end point of production sublevel drifts to drawpoints in open stopes. Also this condition there is chance of loading up to 80% of the broken ore without remote controls (Jimeno 1995). As a result; following development of production sublevel drifts, production drilling, charging and blasting, the blasted ore is prepared to load in drawpoints in the bottom of an open stope. So, the operation will have higher performance to existence of the over 70 degrees dip rate of the major dimension of the ore body. Sublevel stoping is practical to apply in ore bodies which have competent hanging and foot wall rock. Furthermore the ore has to be in a stable situation. Lowest rate of essential compressive strength of the rock walls to apply sublevel stoping is 55 MPa normally. Also sublevel stoping doesn't have a limitation in deep rate. Up to now sublevel stopping method has been applied in depth about 900 m under the surface. In ore bodies which have over 6 m width range, appropriate geometrical form is create to utilize drilling and blasting pattern with high production rate.

Uniformity and regularity in boundaries, dip tendency, shape, width and grade distribution is an essential supposition to choose sublevel stoping method for an ore body. Therefore the implementation selective mining in this method is impossible. Also ideal planning is necessary to smooth production rates. Initial recovery of ore in a stope or pillar block is from 35% to 50% in this method in general (Mann 1998). AS above mentioned, production activities of sublevel stoping method is summarized to achieve production drilling, charging and blasting and then just loading of blasted ore in drawpoints. Therefore the most effective stage on production rate in sublevel stoping sequences would be type of drilling system. In other word the main influential operation stage to define production rate and economical result in a period of time could be associated to select type of drilling system.

Ring drilling and parallel drilling are two main drilling systems in sublevel stoping which have high level productivity. In figure 1 a schematic illustration of ring drilling pattern has been demonstrated in an open stope ('see figure 1.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 radially. Mechanized hydraulic Ring drill rig 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. Longholes don't generally exceed 25 m because hole deviation and manage turn into big problems (Mann 1998). 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 (Gertsch and Bullock 1998). In each blasting 3 or 4 rows are blasted generally. Blast hole spacing is unlike in collars and ends but burden is regular.

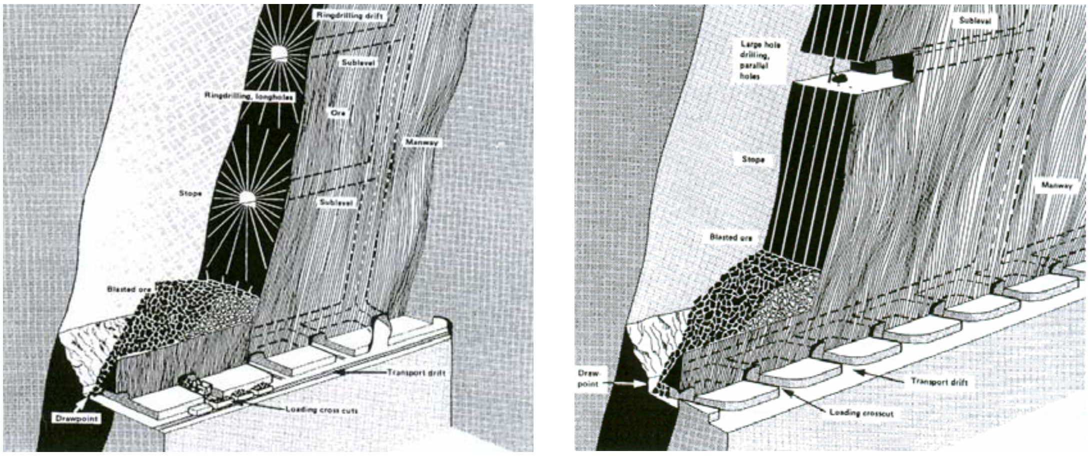

Fig1. Schematic illustration of A.(left): ring drilling, B.(right): parallel drilling

Parallel drilling system is the most recent developed drilling method in sublevel stoping which is possible to perform by mechanized airtrack drill rig with DTH hammer and high pressure. Extending of the endpoint of a production drift is the first stage to implement Parallel drilling system. If so production drift's sides are excavated in width up to thickness of the ore body. Blast holes diameter in parallel drilling is between 105 – 165 mm with lengths up to 90 m. The performance of the drilling system in this respect is about 50 m in a shift. Also ore production range of drilling and blasting related hole lengths is between 8 – 18 m^3/m ('see fig1.B').

In this case blast holes are drilled in bottom of the production drifts downward to drawpoints. In general the inclination of blast holes equals the maximum dip of the ore body. Large diameter Longholes with large scale blasting have been specified in this drilling pattern. This specification is the main cause to appear mass production in sublevel stoping method. Production drifts distance in a vertical alignment in order to implement this system is over 50 meters commonly. Although excavation of one production drift at the top of the open stope is a typical designation. In this case length of the blast holes is defined as the distance of bottom of a production drift to undercutting space. Therefore by execution parallel drilling system, development of production drifts gets the lowest doable cost rate. Also spacing and burden of blast holes regarding large diameter in parallel pattern get to the largest possible range in underground production drilling. Therefore total length of the holes in an open stope reaches to least amount achievable rate. In order to application of mechanized airtrack drill rig with DTH hammer and high pressure, economical condition of sublevel stoping has been changed in the recent decades. Rearding appearance this convenience sublevel stoping has been found more attractive application.

Furthermore there are some other type of long hole drilling pattern which have created of combined parallel and ring drilling properties as underhand fan drilling by DTH jumbodrill rigs. As a case in El Soldado mine underhand fan pattern has been implemented with blast holes' diameter 165 mm and length 80 m by DTH system (Contador and Glavic 2001). High pressure DTH hammers in parallel drilling system have the highest rate of drilling's accuracy. Inaccuracy of this equipment is less than 2% up to 120m hole length of the blast hole in general (Haycocks and Aelick 1992).

3. Economic Comparison of drilling systems

One of the most important stages in sublevel stoping decision making processes is selection of the best alternative of drilling system. 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. The economic consideration has been executed basis of a typical range of assumed ore body different thicknesses and hypothesized different possible heights of a production block.

3.1. The criteria of economic comparing of drilling systems

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

3.2. Procedure of Economic comparison

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

Therefore due to calculation of the total dissimilar cost of each drilling system, the total cost of each production block on the basis of both ring and parallel drilling would be calculate according to 'equation (1)':

$$P = C / V \quad (1)$$

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

Respecting consideration of economic comparison basis of dissimilar, 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 (Pugh and Rsmussen 1982). 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 preventing to cover big space by the name of drilling equipment, the abbreviation M.H.R.D.R. instead of mechanized hydraulic Ring drill rig and DTH M.A.D.R. instead of mechanized airtrack drill rig with DTH hammer and high pressure have been applied.

Table2. Typical drilling and blasting pattern of ring drilling system

Parameter	***Description***	***Quantity***
Hole diameter	51	mm
Drilling rig type	M.H.R.D.	–
The area of vertical cross section of production drifts	3 × 3	m^2
The vertical distance between production drifts	12	m
The horizontal distance between production drifts in each level	Min 6	m
Length of holes	Max 24	m
Spacing at beginning of holes	Min:0.1, often:0.5	m
Spacing at end of holes	Max 2.5	m
Burden	1.5	m
Dip of holes	Max 10 along stope slot	degree
Consumption of ANFO	1.9	Kg/m (hole)
Consumption of primer	0.14	Cartridge/m(hole)
Consumption of cordtex	1.5	m(cordtex/m(hole)

Table3: Typical drilling and blasting pattern of parallel drilling system

Parameter	***Description***	***Quantity***
Hole diameter	152	mm
Drilling rig type	DTH M.A.D.R.	–
Number of production drifts in each stope	1	–
Internal height of production drifts	4	m
Internal width of production drifts	Equal thickness of the ore body	m
Hole length	Max 120	m
Spacing	4	m
Burden	3.7	m
Horizontal distance between last hole of each row and hanging wall and footwall	1.4	m
Number of additional holes in solt	2	–
Consumption of ANFO	13.88	Kg/m(hole)
Consumption of primer	12	Cartridge/m(hole)
Consumption of cordtex	2.5	m(cordtex/m(hole))

The principle of cost calculation is assumed basis of a typical model (Pugh and Rsmussen 1982) according table 4 ('see table 4').

Table4. Typical costs of production drifts development, production drilling and blasting of ring and parallel drilling

Parameter	***Description***	***Quantity***
Cost of production drifts excavation with 3×3 m vertical cross section	12.75	USD/m^3
Cost of production drifts execution with 4m height and minimum 4 m width	12.3	USD/m^3
Cost of production drilling by Mechanized hydraulic Ring drill with 51 mm diameter	2.95	USD/m
Cost of production drilling by DTH jumbo drill with 152 mm diameter	8.2	USD/m
Cost of ANFO	265	USD/ton
Cost of Primer	1.25	USD/cartridge
Cost of Cordtex	1.64	USD/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 would be assumed as follow:

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

Thickness and Dip of ore body is hypothesized basis of achievement high performance sublevel stoping production rate. Due to consideration of economic comparison in various geometrical conditions of ore body and stope designation, calculation of the costs has been carried out on the basis of the detail which is explained in table 5. Height of the production block due to economic comparison consideration is assumed like vertical distance between crown pillar and sill pillar. Regarding to deduction of under cutting space elevation from the vertical distance between mentioned pillars, the fit range of elevation to get high performance production rate is supposed equal 35 to 90 m according to table 5 (‘see table 5’).

Table5. Project of the economic comparison of ring and parallel drilling systems as compared with variation of ore body thickness and height of production block.

Thickness of ore body (m)	***Height of production block (m)***	***Drilling systems***	***Number of stages of economic comparison***	***Number of economic results***
10	30,40,50,60,70,80,90	R1,P	7	14
15	30,40,50,60,70,80,90	R1,P	7	14
20	30,40,50,60,70,80,90	R1,R2,P	7	14
25	30,40,50,60,70,80,90	R1,R2,P	7	14
30	30,40,50,60,70,80,90	R1,R2,R3,P	7	14
35	30,40,50,60,70,80,90	R1,R2,R3,P	7	14
40	30,40,50,60,70,80,90	R1,R2,R3,P	7	14
Total stages			49	147

In all tables as table 5 due to avoid creation big space to refer to some names, abbreviations have been applied. Where P indicates parallel drilling, R_1 indicates ring drilling with one production drift in each sublevel, R_2 indicates ring drilling with two production drifts in each sublevel and R_3 indicates ring drilling with three production drifts in each sublevel. As it’s showed in table 5 to achieve high range required data to carry out economic comparison between drilling systems, 147 stopes were deigned basis of hypothesized stopes’ dimensions. Due to prevent to create a big volume of the text, one designation include thickness of ore body (35 m) and height of production block (90 m) are present as a sample.

In figure 2 the pattern of ring drilling respecting thickness: 35 m, height: 90 m in a vertical cross section view has been illustrated (‘see figure 2’). 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.

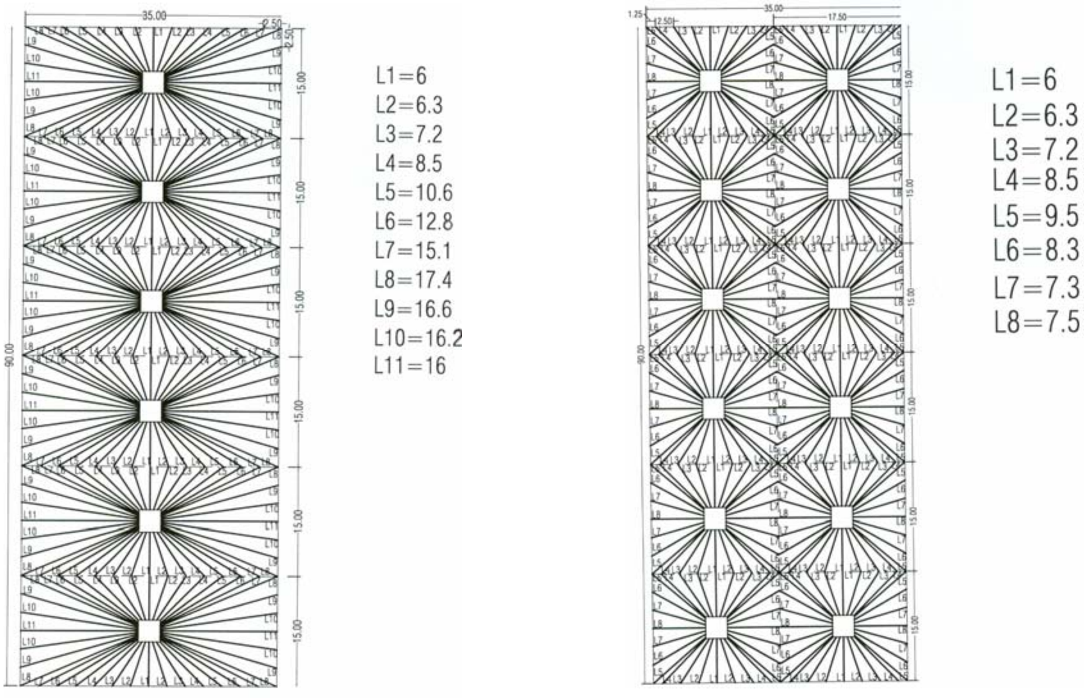

Fig2. A.(left): ring drilling pattern (vertical cross section) in Thickness 35 m and height 90 m with 1 production sublevel drift, B.(right): ring drilling pattern with 2 production sublevel drifts

In all figures L_1, L_2, $L_{3,}$… indicate length of the holes which are illustrated in a vertical cross section on the basis of meter unit. In figure 3 the ring drilling pattern with 3 production drift in each sublevel (vertical cross section) and parallel drilling pattern (horizontal longitudinal section) with respect to Thickness 35 m, height 90 m and Length of stope 90 m has been illustrated ('see figure 3').

In table 6 the final results of designation and calculation of designed stopes in thickness 35 m, height 90 m and length 90 m have been mentioned ('see table 6'). Following designation of the hypothesized stopes and running calculations, final results have been showed. In fact these results are required data to reach economic comparison result between drilling systems.

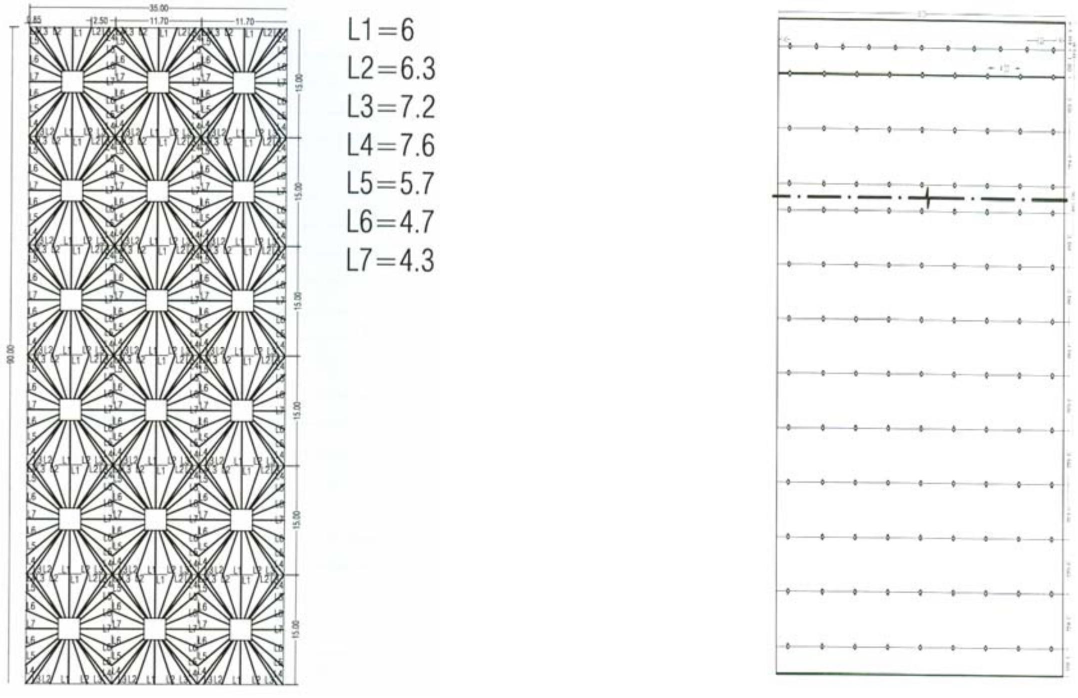

Fig3. A.(left): ring drilling (vertical cross section) in thickness 35 m and height 90 m with 3 production drift in each sublevel, B.(right): parallel drilling (horizontal longitudinal section), Thickness 35m and length of stope 90 m

Table6. Economic comparison of drilling systems in thickness 35m, height 90 m

Parameter	***R_1***	***R_2***	***R_3***	***P***	***Quantity***
Number of production drifts in each stope	6	12	18	1	–
Vertical distance between sublevel drifts	12	12	12	–	m
Number of production drifts in each sublevel	1	2	3	1	–
Horizontal distance between sublevel drifts	–	14.5	8.7	–	m
Area of vertical section in width alignment of production drifts	3 × 3	3 × 3	3 × 3	4 × 35	m^2
Length of each production drift	90	90	90	90	m
Total internal volume of production drifts	4860	9720	14580	12600	m^3
Cost of excavation of production drifty	12.7	12.7	12.7	12.3	USD/m^3

Parameter	***R1***	***R2***	***R3***	***P***	***Quantity***
Total cost of excavation of production drifts in a stope	62000	123400	185200	155000	USD
Hole diameter	51	51	51	152	mm
Drilling rig	M.H.R.D.			DTH M.A.D.R.	–
Spacing	0.2 – 2.5	0.4 – 2.5	0.2 – 2.5	4	m
Burden	1.5	1.5	1.5	3.6	m
Number of holes in a stope	14400	20200	25900	227	–
Length of holes	6 – 17.5	6 – 9.5	4.3 – 7.6	86	m
Total length of holes in a stope	175320	156000	158400	19500	m
Cost of production drilling	3	3	3	8.2	USD/m
Total cost of production drilling in a stope	517000	468000	475000	16000	USD
Consumption of ANFO	328	292	296	271	Ton
Consumption of Primer	25070	22320	22660	2720	Cartridge
Consumption of Cordtex	270000	240000	244000	48800	m
Total cost of explosives	561000	499500	507000	155000	USD
Total costs	1140000	1091000	1167200	470000	USD
Volume of extracted ore from excavation of drifts	4860	9720	14580	12600	In situ m^3
Volume of blasted ore	278640	273780	268920	270900	In situ m^3
Total volume of extracted ore	283500	283500	283500	283500	In situ m^3
Cost of extraction	4	3.8	4.1	1.7	USD/m^3
Percentage of cost in P/R	42	45	41		%
Percentage of drilling time in P/R	42	47	47		%

In the next stage of economic comparison basis of comparison of possible designations results in each assumed thickness of ore body and height of production block, 49 comparing geometrical condition is resulted. In each comparing condition with respect to specific height and thickness possible drilling systems are seen. Also the amount of dissimilar cost of viable drilling system due to USD/m^3 of in situ ore is seen to create simple situation of comparing of executions ('see table 7').

Table7. Results of 49 stages of designing and calculating for economic comparison of drilling systems in different ore body and production block condition

Dissimilar cost (USD/m^3)				***Height (m)***	***Thickness (m)***
P	R_3	R_2	R_1		
2.9	–	–	3.7	30	10
2.5	–	–	3.7	40	10
2.3	–	–	3.9	50	10
2.1	–	–	3.7	60	10
2	–	–	3.7	70	10
1.9	–	–	3.8	80	10
1.9	–	–	3.7	90	10
2.7	–	–	3.5	30	15
2.3	–	–	3.6	40	15
2.1	–	–	3.8	50	15
2	–	–	3.5	60	15
1.9	–	–	3.6	70	15
1.8	–	–	3.7	80	15
1.7	–	–	3.5	90	15
2.8	–	3.7	3.6	30	20
2.5	–	3.7	3.6	40	20
2.2	–	3.9	3.7	50	20
2.1	–	3.7	3.6	60	20
2	–	3.7	3.6	70	20
1.9	–	3.8	3.6	80	20
1.8	–	3.7	3.6	90	20
2.8	–	3.9	3.7	30	25
2.4	–	4	3.8	40	25
2.2	–	4.1	3.9	50	25
2	–	3.9	3.7	60	25
1.9	–	3.9	3.7	70	25
1.82	–	4	3.8	80	25
1.8	–	3.9	3.7	90	25
2.7	–	3.5	3.8	30	30
2.3	–	3.6	4	40	30
2.1	–	3.8	4.1	50	30
1.9	–	3.5	3.8	60	30
1.8	– 3.6	3.9	70	30	
1.8	– 3.7	4	80	30	

1.7	–	3.5	3.8	90	30
2.7	4.09	3.8	4	30	35
2.3	4.13	3.9	4.2	40	35
2.1	4.29	4	4.3	50	35
1.9	4.09	3.8	4	60	35
1.8	4.11	3.9	4.1	70	35
1.72	4.22	4	4.2	80	35
1.7	4.09	3.8	4	90	35
2.7	3.78	3.6	4.2	30	40
2.4	3.84	3.6	4.4	40	40
2.14	3.98	3.7	4.5	50	40
2	3.78	3.6	4.2	60	40
1.9	3.8	3.6	4.3	70	40
1.8	3.91	3.7	4.4	80	40
1.7	3.78	3.6	4.2	90	40

Regarding creation of final result relating to dissimilar cost of execution of the doable drilling system, comparing of drilling systems would be possible in unlike thickness range of ore body. Therefore essential material to select 1^{st,} 2nd and 3rd choices has been obtained ('see table 8'). According table 8 in all thickness range of ore body, parallel drilling with the lowest cost rate is the 1st choice. Also it is realized that 2nd choice in different thickness up to 30 m would be ring drilling pattern with 1 production sublevel drift. As well in thicknesses over 30 m ring drilling with 2 production sublevel drift would be 2nd alternative.

Table8. Selection of preferences on drilling choice in different thicknesses

Thickness (m)	***1st choice***	***2nd choice***	***3rd choice***	***4th choice***
10 – 20	P	R_1	–	–
20 – 30	P	R_1	R_2	–
30 – 35	P	R_2	R_1	–
35 – 40	P	R_2	R_1	R_3
40	P	R_2	R_3	R_1

4. Conclusion

As said by reach results it was proved that type of production drilling is effective on production sublevel drifts development, drilling rate and explosives consumption costs. So as to existing high performance production rate of ring and parallel drilling systems opposed to other conventional drilling system of sublevel stoping, in economic comparing consideration would be included just both mentioned drilling systems. Regarding 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 economic comparison of drilling systems in sublevel stoping method 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 aim of apply parallel drilling, dissimilar production costs are decreased about 45% in opposition to execute of ring drilling generally.

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