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A New Technical and Economic Model to Calculate Specific Charge and Specific Drilling Using Hole Diameter, Bench Height, Uniaxial Compressive Strength, and Joint Set Orientation

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Abstract

Calculation of the specific charge and specific drilling before a blasting operation plays a significant role in the design of a blasting pattern and the reduction of the final extraction cost of minerals. In this work, the information from the Sungun, Miduk and Chah-Firouzeh copper mines in Iran was assessed, and it was found that there was a significant relationship between the specific charge and specific drilling and the hole diameter, bench height, uniaxial compressive strength and joint set orientation. After finding a technical and economic model to calculate the specific charge and specific drilling, this model was tested on the Sungun copper mine. Due to the insufficient consideration during the design of a blast pattern and because of the high hardness of the rocks in some parts of the mine, lots of destructive events such as boulders, back break, bench toe, high specific charge and high specific drilling, fly rock, and ground vibration in the blast operations were observed. The specific charge and specific drilling were found to be the most important technical and economic parameters involved in designing a blasting pattern, and they were found to play an important role in reducing the blasting cost. The blasting cost could be largely controlled by the accurate examination and computation of these parameters. An increase in the rock strength and the angle between the bench face and the main joint set would increase the specific charge and specific drilling. On the other hand, a specific charge and a specific drilling would decrease when the hole diameter increased in every range of the uniaxial compressive strength..

1. Introduction

Blasting models were formulated by applying the technical and economic information to the blasting operations at three large copper mines in Iran, namely Sungun, Miduk, and Chah-Firouzeh. After finding a technical and economic model to calculate the specific charge and specific drilling, this model was tested on the Sungun copper mine. The Sungun copper ore is located in the volcanic zone of Orumieh-Dokhtar in Iran and it is a part of Alps-Himalayas. The Sungun mineral zone is, in fact, the intrusive zone, semi-deep and porphyry of Sungun that is also the host of copper ore and molybdenum porphyry. This zone is an area of around 50 square kilometers [1]. According to the research works, the Sungun porphyry copper is almost located in the potassic alteration zone. The uniaxial compressive strength of monzonite rocks is 120-180 MPa, and quartz monzonite has been measured to be more than 180 MPa. The other alteration rocks of the zone including argillic, phyllic, and propylitic have a strength of less than 120 MPa [2]. Figure 1 shows a typical perspective view of the Sungun copper mine in Iran.

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Figure 1. A typical perspective view of the Sungun copper mine.

One of the most important operations carried out in mining is blasting [3, 4, 5]. Blasting is still an economical and viable method for rock excavation in the mining and civil work projects. The major areas of blasting operations are productivity, environmental effects, and safety. Productivity is related to obtaining the desired fragmentation with a uniform or appropriate size and a proper displacement of rocks [6]. Blasting at open pits is potentially a dangerous operation if it is not carried out in accordance with the regulations and if all the necessary protection measures are not undertaken [7]. Selecting a suitable pattern causes to reduce the blasting costs and operational problems in the mining stages[8]. Reduction of the blast operation cost is very important for the cost price of the final product. A suitable blasting pattern should be economically and technically acceptable [3, 9]. So far, the mean size of fragmentation has been considered as the main factor involved in the evaluation of blasting patterns [10, 11, 12, 13]. Selecting the blasting patterns by only regarding the fragmentation size factor causes neglecting the effects of the other technical parameters such as back break, fly rock, ground vibration, and air blast where these effects lead to some problems in mines [14]. Back break has been known as a destructive phenomenon in mines, and thus the designers attempt to forecast and prevent this problem in the new blasting bench [15, 16, 17, 18, 19]. In order to achieve a reasonable fly rock distance for providing safety in mines, decrease in the fly rock is one of the main worries of the blasting designers [20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30]. In some cases, with increase in the specific charge, ground vibration and air blast have caused some problems in mines, so a designer should calculate the specific charge before blasting [31, 32, 33, 34, 35, 36, 37]. In order to predict and calculate the fragmentation and fly rock in the Sungun copper mine, Ghibi *et al*. have determined that the modified Kuz-Ram method predics the fragment size distribution better than the Kuz-Ram model [38]. Faramarzi *et al*., using the RES (Rock Engineering System) method and comparing it with the multiple regression models and the Kuz-Ram model, have found that the RES method is more accurate than the previous ones in predicting fragmentation [39]. In the discussion of fly rock and back break, Ghasemi *et al*. have predicted the amount of fly rock in the Sungun copper mine by applying the Monte Carlo method [25]. Although the fragmentation parameter is important in the blasting costs, other parameters such as the specific charge and specific drilling can play a more important role in the blasting costs. In a research work, Gh. Zarghami *et al*. have studied the most important economic parameters by the ANP method in a blast operation in surface mines. It was determined that the specific charge, specific drilling, fragmentation, back break, ground vibration, fly rock, and air blast were, respectively, the most important economic blast parameters [40]. Therefore, in this research work, by the reform of designing, the specific charge and specific drilling and the destructive events were decreased in the Sungun copper mine.

In another study, by investigating and analyzing the blast information for the Sungun, Miduk, and Chah-Firouzeh copper mines in Iran, it was determined that there was a function between the specific charge and the burden. This function is $\boldsymbol{B = a(SC)^2 + b(SC) + C}$, where "a", "b", and "c" are different according to the type and material of the stones [41]. During these years, the researches of the blasting science have done lots of activities by studying the articles and carrying out similar research works to decrease the blasting operation cost. Afum and Temeng have explored various parameters affecting the drilling cost reduction and blast optimization in a gold mine in Qana. At this mine, the blasts were done in three different blocks. The parameters including the ground conditions and blast pattern affected the blasting and crushing costs. The model was employed in order to regulate the costs by testing the suggested patterns. The results obtained indicted a decrease in the ranges of 5.3 - 12.2% in the ore costs and 2.9 - 14.8% for waste removal costs [42]. Adebayo and Akande have investigated the effects of drilling in terms of the blast-hole deviation and muck-pile loading costs for six scenarios at Hwange Colliery, Zimbabwe.

The study showed that the drilling and operational costs were in the range of US$0.13–7.53 per m^3. Ancillary costs of drilling increased from US$1.7 to US$4.2 per m^3 with an increase in the blast-hole deviation from 7% gradient to 21% [43]. Adebayo and Mutandwa have evaluated the relationship between the blast-hole deviation, fragment size, and fragmentation cost. The use of ANFO, heavy ANFO, and emulsion explosives in holes of 191 mm and 311 mm in diameter was compared using six scenarios. The results obtained showed that as the blast-hole deviation increased, the mean fragment size decreased and the cost of drilling and blasting increased. Increasing the hole diameter from 191 mm to 311 mm decreased the blast fragmentation [44]. Nenuw and Jimoh have designed and optimized the blasting parameters to reduce the damaging effects and blasting costs using the Langfors and other common blast formulae. In this work, which was conducted at four mines, the parameters such as burden, spacing, bench height, hole diameter, the number of holes, bottom charge, and total charge per hole were examined, and the planned and actual costs were calculated. The actual costs of blasting materials were higher than the calculated ones, and required modification and revision [45]. Cunningham has investigated four key parameters that determine the ability to design an effective blast in terms of delay time and cost. These parameters included heave control and monitoring, hole diameter, and explosive type [46]. Strelec, Gazdek, and Mesec have designed an optimized blast pattern to reduce the drilling costs. The blast fragmentation was optimized by applying the calibration factors in the Kuz-Ram model [47]. Alipour and Ashtiani, regarding the fuzzy approach, have presented a model to predict the maximum charge per delay in the Sungun Copper mine. In this modeling, a maximum charge per delay was considered as an output parameter for maximum peak particle velocity (PPV) in the blasting predicted, which determined that the model results were closer to the actual values [48].

1.1. History of specific charge models

In 1954, Frankel proposed a specific charge calculation model based on the blastability index (BI). In this model, the strength of rock was not considered and more attention was paid to the geometric parameters of the blasting pattern [49]. In 1968, Hansen introduced a relationship for calculating the amount of explosives in each hole, in which the burden and hole height were considered as the main parameters [49]. In 1973, Larson proposed a model based on the dimensions of mesh, in which the burden and spacing parameters were considered as the main parameters [50]. In 1973, Kuznetsov provided a model based on the amount of the TNT explosive material, and the rock geomechanical characteristics were among the main parameters [51]. The Lundborg model was introduced in 1973 as an experimental model based on the throw length of the rock and the hole diameter [51]. In 1976, Heinen and Dimock, based on the correlation between crushed rock, specific charge, and wave propagation velocity, provided a direct relationship between the specific charge and the vibration wave propagation velocity [49]. In 1981, Ashby provided a model based on the internal friction angle and the internal crack length in the rock [52]. In 1981, Borquez presented a model based on the blastability index (BI) and RQD [49]. In 1982, Leighton presented a relationship based on RQI (Rock Mass Quality Index), drill hydraulic pressure, and drilling time [49]. The KUZ-RAM model was introduced in 1983 based on the rock factor and the amount of TNT explosive and the relative weight of the explosives and the blasted rock volume [53]. In 1984, Jimeno presented a relationship based on the drilling index and permeability velocity in rock and hole diameter [49]. In 1985, Berta presented a relationship based on the rock impedance coefficient and the coupling coefficient and energy transferred to the rock [54]. In 1986, Lilly, based on the blastability index (BI) and the geomechanical conditions of the rock mass, provided a relationship for the iron ore mines of Western Australia [55]. In 1987, KUZ-RAM provided a relationship based on the blastability index (BI), average dimensions of crushed rocks, amount of TNT explosives, and relative weight of the explosives [51]. In 1989, a model was introduced in Fragblast to calculate the specific charge based on the mesh size, TNT value of each hole, ratio of burden and spacing, hole height, and hole diameter [56]. In 1990, Gupta provided a model based on the burden and Partodiakenov strength index, UCS Index, and elastic modulus in underground mines [49]. In 1992, Persson, Holemborg, and Lee presented a model based on burden which was very simple [51]. In 1992, Rusten provided an exponential model based on RQD, burden, spacing, wave velocity, and number of joints [57]. In 1993, Svedefo presented a model based on the mesh size, hole depth, and burden as an exponential function [50]. Over the years, the experimental charts such as the Dupont chart have been presented, which today do not have the necessary efficiency to calculate the specific charge [58]. Since 2002, some models have been proposed based on the search algorithms such as neural network algorithms and genetic algorithms, each of which has been presented in a special mine based on the special conditions of that mine.

2. Investigation of blasting database and supplying a new model

The large number of factors and the complicated iterations make it impossible to determine the theoretical consumption of explosives at the present level of development in the blasting theory. Thus recourse is made either to the practical data or to the empirical formulae that generalize the blasting practice in application to drifting [59]. In the present research work, the four important parameters hole diameter, UCS, joint set orientation, and bench height were selected for calculating a model. These parameters could be easily calculated by the engineers, and ultimately aid in estimation. More than 4600 records of blasting operations at the Sungun, Miduk, and Chah-Firouzeh mines were collected from 2012 to 2014. The incorrect and unreliable records were deleted, and finally, around 2414 blasts with minimum back break, air blast, ground vibration, oversize, and destructive effects were selected. The correct ratios between the geometric parameters of blasting patterns and hole diameter in the UCS range of 10 - 250 MPa and for the angle between the bench face and main joint set (γ) <90° and >90° were extracted from the blasting databases at the respective mines. According to the rules of the block theory, the angle between the bench face and the main joint set is important. This angle is located between the two normal vectors of the planes. In other words, γ is the same angle between the two planes, and it is a necessary factor for writing the equation of plane, dip, and dip direction of the plane [2]. These ratios are presented in Tables 1 and 2. In the same UCS range, more energy is required when γ is greater than 90° because the joint set dips are in the opposite direction to the free face direction. Therefore, the specific charge, specific drilling, and blasting costs are higher for γ>90° than for γ<90° [2]. In these tables, the burden (B), spacing (S), stemming (T), and sub-drilling (J) are the important geometric parameters of the blasting pattern.

Table 1. Ratio between the geometric parameters and hole diameter for ($\gamma < 90^{\circ}$) [2].

UCS (Mpa)	10-70 MPa				70-120 MPa				120-180 MPa				180-250 MPa			
Limit	Min	Max	Mean	σ	Min	Max	Mean	σ	Min	Max	Mean	σ	Min	Max	Mean	σ
B/Dh (m/in)	0.99	1	0.99	0.003	0.915	0.945	0.93	0.0103	0.882	0.918	0.9	0.0104	0.821	0.859	0.84	0.014
S/Dh (m/in)	1.29	1.31	1.3	0.008	1.185	1.195	1.19	0.0035	1.082	1.118	1.1	0.0102	0.941	0.979	0.96	0.0106
T/Dh (m/in)	0.89	0.91	0.9	0.007	0.825	0.855	0.84	0.0108	0.792	0.828	0.81	0.012	0.731	0.769	0.75	0.0103
J/Dh (m/in)	0.24	0.26	0.25	0.009	0.255	0.285	0.27	0.0106	0.282	0.318	0.3	0.013	0.281	0.319	0.3	0.0104

Table 2. Ratio between the geometric parameters and hole diameter for ($\gamma > 90^{\circ}$) [2].

UCS (Mpa)	10-70 MPa				70-120 MPa				120-180 MPa				180-250 MPa			
Limit	Min	Max	Mean	σ	Min	Max	Mean	σ	Min	Max	Mean	σ	Min	Max	Mean	σ
B/Dh (m/in)	0.699	1.161	0.93	0.211	0.599	1.201	0.9	0.291	0.81	0.87	0.84	0.028	0.76	0.8	0.78	0.0104
S/Dh (m/in)	1.18	1.2	1.19	0.007	0.899	1.301	1.1	0.187	0.94	0.98	0.96	0.018	0.794	0.866	0.83	0.033
T/Dh (m/in)	0.828	0.852	0.84	0.0107	0.78	0.84	0.81	0.0219	0.725	0.775	0.75	0.022	0.47	0.93	0.7	0.21
J/Dh (m/in)	0.24	0.3	0.27	0.023	0.299	0.301	0.3	0.0007	0.28	0.32	0.3	0.0109	0.27	0.33	0.3	0.023

Then by geometric modeling of the blasting block with different heights less than 30 m, the width of 70 m and the length of 150 m, the relations between the hole diameter and specific charge and specific drilling in the hole diameter of 2 to 16 inches, and the rock strength of 10 up to 250 MPa were obtained. Tables 3 to 6 and Figures 2 to 5 define the above relations for ($\gamma < 90^{\circ}$) and Table 8 is presented for ($\gamma > 90^{\circ}$) according to the calculations of Table 9. By geometric calculating the blasting data within the scope of uniaxial compressive strength and by model of hole different diameters from 2 to 16 inches and the height of block from 10 to 30 m, the linear model $SC = a(Dh) + b$ between hole diameter in inches and specific charge in terms of kilograms per cubic meter was established for ANFO with a special weight of 0.88 ton/m^3. In this regard, the coefficients ‘a’ and ‘b’ were changed according to the block height changes and the uniaxial compressive strength, and a logarithmic relationship between coefficients ‘a’, ‘b’ and the block height was established, and with modeling of different hole diameters from 2 to 16 inches and bench height of 5 to 30 m, the power model of $SD = a(Dh)^{-b}$ was formed between the hole diameter in inches and the specific drilling in meters per cubic meter. In this equation, the coefficients ‘a’ and ‘b’ change with changes in the block height and the uniaxial compressive strength, and a logarithmic relationship is formed between the coefficients ‘a’ and ‘b’ with block height.

Table 3. Calculations of blasting parameters, specific charge, specific drilling with (UCS 10-70 MPa, $\gamma < 90^{\circ}$) and hole diameter between 2 and 16 inch.

10-70 MPa		Dh (in)	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Ratio rounded (m/in)		Dh (mm)	50.8	76.2	102	127	152	178	203.2	228.6	254	279.4	304.8	330.2	355.6	381	406.4
B/Dh	0.99	B (mm)	1980	2970	3960	4950	5940	6930	7920	8910	9900	10890	11880	12870	13860	14850	15840
S/Dh	1.3	S (mm)	2574	3861	5148	6435	7722	9009	10296	11583	12870	14157	15444	16731	18018	19305	20592
T/Dh	0.9	T (mm)	1782	2673	3564	4455	5346	6237	7128	8019	8910	9801	10692	11583	12474	13365	14256
J/Dh	0.25	J (mm)	495	742.5	990	1237.5	1485	1732.5	1980	2227.5	2475	2722.5	2970	3217.5	3465	3712.5	3960
SC (Kg/m^3)			0.32	0.3	0.29	0.27	0.26	0.24	0.2294	0.21439	0.1994	0.1844	0.1694	0.154	0.1394	0.124	0.109
SD (m/m^3)			0.2	0.09	0.05	0.03	0.02	0.02	0.0139	0.01112	0.0091	0.00766	0.0065	0.006	0.0049	0.004	0.004

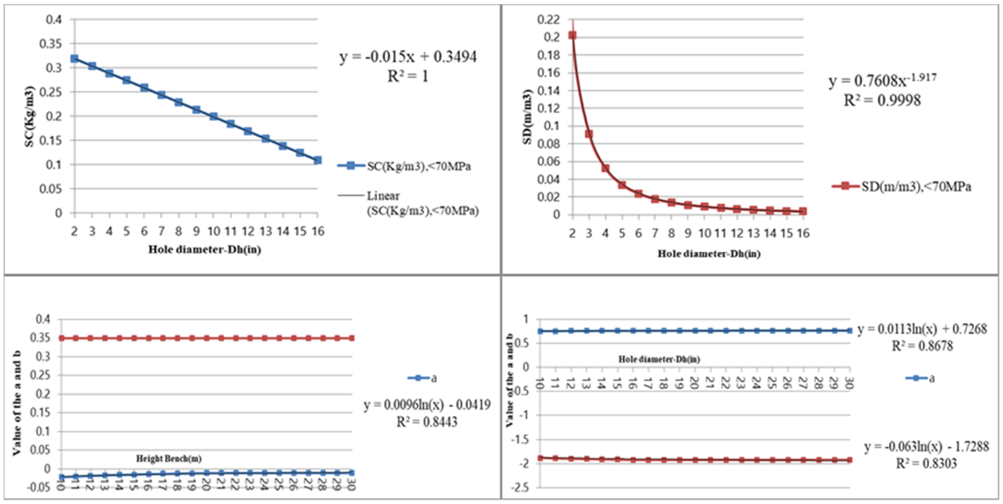

Figure 2. Relationship of specific charge and specific drilling with hole diameter changes and relations of a and b considering changes of bench height in UCS 10-70 MPa.

Table 4. Calculations of blasting parameters, specific charge, specific drilling with (UCS 70-120 MPa, $\gamma < 90^{\circ}$) and hole diameter between 2 and 16 inch.

70-120 MPa		Dh (in)	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Ratio rounded(m/in)		Dh (mm)	50.8	76.2	102	127	152	178	203.2	228.6	254	279.4	304.8	330.2	355.6	381	406.4
B/Dh	0.93	B (mm)	1860	2790	3720	4650	5580	6510	7440	8370	9300	10230	11160	12090	13020	13950	14880
S/Dh	1.19	S (mm)	2380.8	3571.2	4761.6	5952	7142.4	8332.8	9523.2	10713.6	11904	13094.4	14284.8	15475.2	16665.6	17856	19046.4
T/Dh	0.84	T (mm)	1674	2511	3348	4185	5022	5859	6696	7533	8370	9207	10044	10881	11718	12555	13392
J/Dh	0.27	J (mm)	539.4	809.1	1078.8	1348.5	1618.2	1887.9	2157.6	2427.3	2697	2966.7	3236.4	3506.1	3775.8	4045.5	4315.2
SC(Kg/m^3)			0.372	0.357	0.342	0.326	0.311	0.296	0.281	0.266	0.250	0.235	0.220	0.205	0.189	0.174	0.159
SD(m/m^3)			0.234	0.106	0.061	0.039	0.028	0.021	0.016	0.013	0.011	0.009	0.008	0.007	0.006	0.005	0.005

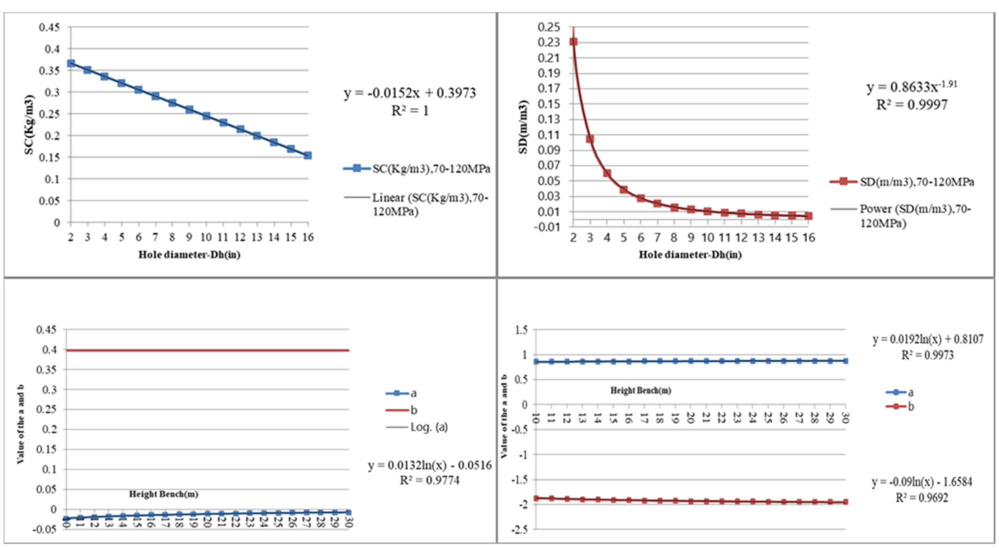

Figure 3. Relationship of specific charge and specific drilling with hole diameter changes and relations of a and b considering changes of bench height in UCS 70-120 MPa.

Table 5. Calculations of blasting parameters, specific charge, specific drilling with (UCS 120-180 MPa, $\gamma < 90^{\circ}$) and hole diameter between 2 and 16 inch.

120-180 MPa		Dh (in)	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Ratio rounded (m/in)		Dh (mm)	50.8	76.2	102	127	152	178	203.2	228.6	254	279.4	304.8	330.2	355.6	381	406.4
B/Dh	0.9	B (mm)	1800	2700	3600	4500	5400	6300	7200	8100	9000	9900	10800	11700	12600	13500	14400
S/Dh	1.1	S (mm)	2196	3294	4392	5490	6588	7686	8784	9882	10980	12078	13176	14274	15372	16470	17568
T/Dh	0.81	T (mm)	1620	2430	3240	4050	4860	5670	6480	7290	8100	8910	9720	10530	11340	12150	12960
J/Dh	0.3	J (mm)	594	891	1188	1485	1782	2079	2376	2673	2970	3267	3564	3861	4158	4455	4752
SC(Kg/m^3)			0.43	0.42	0.4	0.39	0.37	0.35	0.3395	0.32416	0.3088	0.29348	0.2781	0.263	0.2475	0.232	0.217
SD(m/m^3)			0.27	0.12	0.07	0.05	0.03	0.02	0.0188	0.01513	0.0125	0.01047	0.0089	0.008	0.0068	0.006	0.005

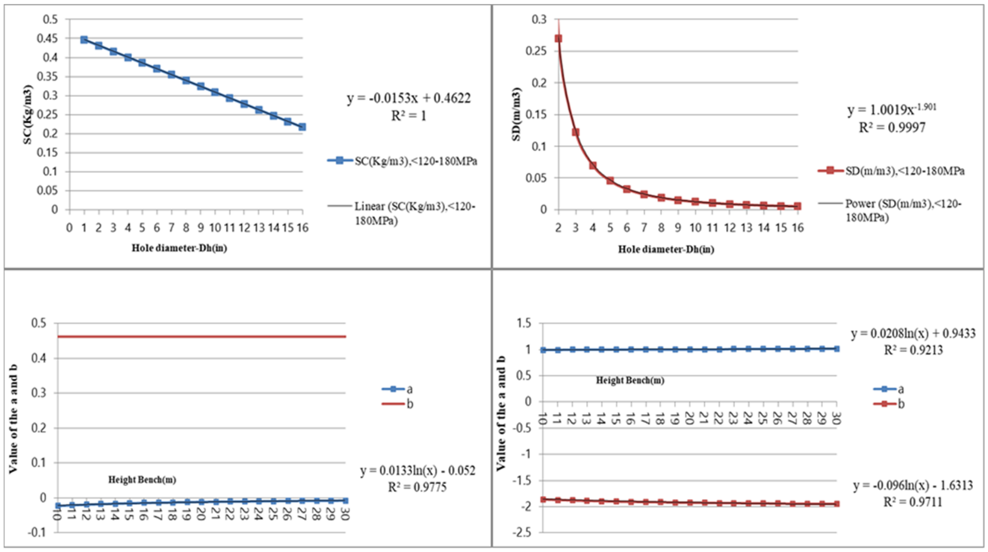

Figure 4. Relationship of specific charge and specific drilling with hole diameter changes and relations of a and b considering changes of bench height in UCS 120-180 MPa.

Table 6. Calculation of blasting parameters, specific charge, specific drilling with (UCS 180-250 MPa, $\gamma < 90^{\circ}$) and hole diameter between 2 and 16 inch.

180-250MPa		Dh (in)	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Ratio rounded (m/in)		Dh (mm)	50.8	76.2	102	127	152	178	203.2	228.6	254	279.4	304.8	330.2	355.6	381	406.4
B/Dh	0.84	B (mm)	1680	2520	3360	4200	5040	5880	6720	7560	8400	9240	10080	10920	11760	12600	13440
S/Dh	0.96	S (mm)	1915.2	2872.8	3830.4	4788	5745.6	6703.2	7660.8	8618.4	9576	10533.6	11491.2	12448.8	13406.4	14364	15321.6
T/Dh	0.75	T (mm)	1495.2	2242.8	2990.4	3738	4485.6	5233.2	5980.8	6728.4	7476	8223.6	8971.2	9718.8	10466.4	11214	11961.6
J/Dh	0.3	J (mm)	599.76	899.64	1199.52	1499.4	1799.28	2099.16	2399.04	2698.92	2998.8	3298.68	3598.56	3898.44	4198.32	4498.2	4798.08
SC(Kg/m^3)			0.52	0.5	0.49	0.47	0.45	0.44	0.4184	0.4018	0.3852	0.36851	0.3519	0.335	0.3186	0.302	0.285
SD(m/m^3)			0.32	0.15	0.08	0.05	0.04	0.03	0.0225	0.01805	0.0149	0.01249	0.0107	0.009	0.0081	0.007	0.006

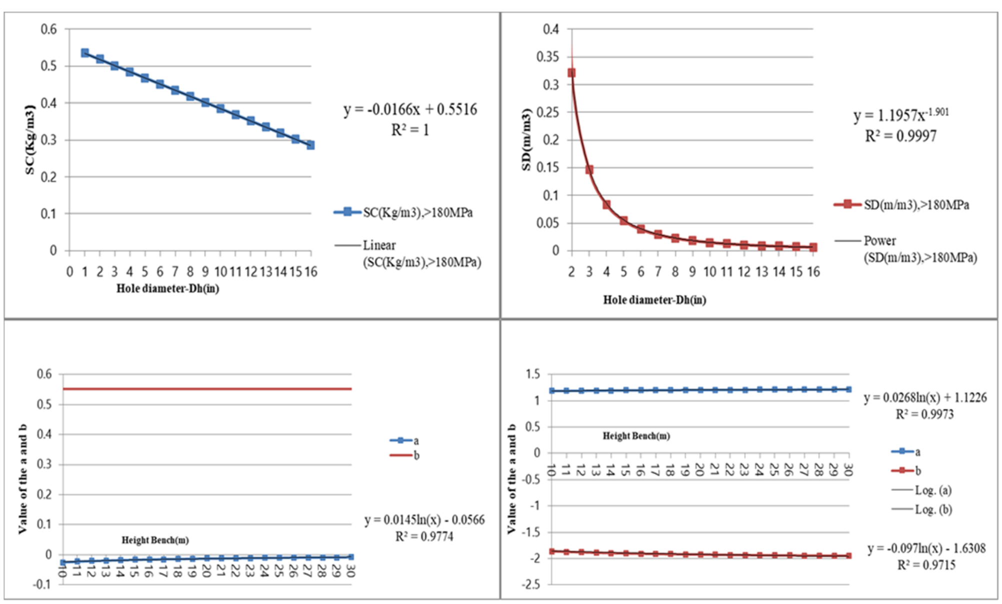

Figure 5. Relationship of specific charge and specific drilling with hole diameter changes and relations of a and b considering changes of bench height in UCS 180-250 MPa.

All blasting costs were modeled in the COMFAR technical and economic analysis software, and the cost per cubic meter of rock was calculated. As presented in Table 7, 87% of the blasting operation costs depend on the cost of ANFO and drilling costs. Equation [1] shows the cost of blasting operations according to the specific drilling, specific charge, price per kilogram of ANFO, and drilling cost per meter [2].

C1 + C2= 87%BC

BC = (1/ 0.87)(PA × SC + PD × SD) =1.15(PA × SC+ PD × SD) (1)

In Equation [1], the parameter C1 represents the ANFO cost, C2 represents the drilling cost, BC represents the blasting cost per cubic meter, PA is the price of ANFO per kilogram, PD is the price of drilling per meter, SC is the specific charge (kg/m^3), and SD is the specific drilling (m/m^3).

Table 7. The ratio of ANFO costs and drilling costs to the total blasting costs [2].

No.	Mine name	Type	year	Blasting Cost (1000Rials/m^3)	Production Volumes (m^3)	Anfo Cost + Drilling Cost (1000Rials) (A)	Drilling Cost (1000Rials)	Anfo Cost (1000Rials)	Total Blasting Cost (1000Rials) (B)	Ratio A/B
1	Miduk	Waste	2012	13.67	3,931,645	48,863,950	16,528,950	32,335,000	53,739,619	91%
2	Miduk	Waste	2013	14.83	2,460,168	33,736,800	10,861,800	22,875,000	36,487,558	92%
3	Miduk	Waste	2014	14.07	1,021,837	12,349,950	3,627,450	8,722,500	14,377,475	86%
4	Miduk	Mixed	2012	14.32	1,952,261	23,644,850	8,024,850	15,620,000	27,959,571	85%
5	Miduk	Mixed	2013	15.42	2,802,693	38,499,100	11,924,100	26,575,000	43,215,594	89%
6	Miduk	Mixed	2014	13.27	5,981,862	72,757,900	22,107,900	50,650,000	79,380,906	92%
7	Miduk	Ore	2012	15.05	1,430,466	15,393,550	5,176,050	10,217,500	21,529,271	72%
8	Miduk	Ore	2013	21.81	1,010,146	13,553,350	4,679,100	8,874,250	22,027,611	62%
9	Miduk	Ore	2014	18.79	1,002,165	11,914,000	3,939,000	7,975,000	18,831,301	63%
10	Sungun	Waste	2012	32.18	624,178	18,668,700	6,610,950	12,057,750	20,085,600	93%
11	Sungun	Waste	2013	34.62	147,914	3,914,725	1,410,450	2,504,275	5,120,925	76%
12	Sungun	Waste	2014	40.21	315,153	11,390,050	4,014,000	7,376,050	12,672,690	90%
13	Sungun	Ore	2012	13.52	7,698,287	101,487,100	35,356,350	66,130,750	104,078,530	98%
14	Sungun	Ore	2013	14.19	6,777,431	93,713,950	32,721,450	60,992,500	96,188,900	97%
15	Sungun	Ore	2014	14.37	6,562,884	91,971,600	31,918,800	60,052,800	94,300,530	98%
16	Chah-Firouzeh	Waste	2012	18.12	2,702,430	45,956,250	15,142,500	30,813,750	48,973,369	94%
17	Chah-Firouzeh	Waste	2013	15.32	3,742,393	54,760,000	21,303,750	33,456,250	57,345,636	95%
18	Chah-Firouzeh	Waste	2014	13.39	3,098,502	39,060,050	13,063,800	25,996,250	41,480,320	94%
			*In 2017: 1$ = 37000 Rials Iran's currency is the Rial					Mean:		87.01%

As a result, Table 8 and 9 show a new model to calculate the specific charge and specific drilling in the Sungun copper mine. In these Tables, the relations of specific charge and specific drilling can be used in prediction of the specific charge and specific drilling before a blasting pattern design.

Table 8. Calculation of blasting pattern parameters and anticipation new model of ANFO specific charge and specific drilling in the case ($\gamma < 90^{\circ}$).

UCS (MPa)	10-70 MPa	70-120 MPa	120-180 MPa	180-250 MPa
BC ($/$m^3$) BC = 1.15 ($P_A$ × SC + P_D × SD)	BC = 1.15 (P_A × SC + P_D × SD)	BC = 1.15 (P_A × SC + P_D × SD)	BC = 1.15 (P_A × SC + P_D × SD)	BC = 1.15 (P_A × SC + P_D × SD)
SC (Kg/m^3)	a(Dh) + b a = 0.0096ln(H) - 0.0419 b = 0.3494	a(Dh) + b a = 0.0132ln(H) - 0.0516 b = 0.3973	a(Dh) + b a = 0.0133ln(H) - 0.052 b = 0.4622	a(Dh) + b a = 0.0145ln(H) - 0.0566 b = 0.5516
SD (m/m^3)	$a(Dh)^{-b}$ a = 0.0113ln(H) + 0.7268 b = 0.063ln(H) + 1.7288	$a(Dh)^{-b}$ a = 0.0192ln(H) + 0.8107 b = 0.09ln(H) + 1.6584	$a(Dh)^{-b}$ a = 0.0208ln(H) + 0.9433 b = 0.096ln(H) + 1.6313	$a(Dh)^{-b}$ a = 0.0268ln(H) + 1.1226 b = 0.097ln(H) + 1.6308
B (m)	0.99 Dh	0.93 (Dh)	0.9 (Dh)	0.84 (Dh)
S (m)	1.3 (Dh)	1.19 (Dh)	1.1 (Dh)	0.96 (Dh)
T (m)	0.9 (Dh)	0.84 (Dh)	0.81 (Dh)	0.75 (Dh)
J (m)	0.25 (Dh)	0.27 (Dh)	0.3 (Dh)	0.3 (Dh)

Dh: Hole Diameter (in) UCS: Uniaxial Compressive Strength (MPa) BC: Blasting Cost ($/$m^3$)
SC: Specific Charge (Kg/m^3) SD: Specific Drilling (m/m^3) H: Bench height (m)
P_A: Price Anfo ($/Kg) P_D: Price Drilling ($/m)
γ : Angle between plane of bench face and the plane of main joint set

Table 9. Calculation of blasting pattern parameters and anticipation new model of ANFO specific charge and specific drilling in the case ($\gamma > 90^{\circ}$).

UCS (MPa)	10-70 MPa	70-120 MPa	120-180 MPa	180-250 MPa
BC ($/$m^3$) BC = 1.15($P_A$× SC + P_D× SD)	BC = 1.15(P_A× SC + P_D×SD)	BC = 1.15(P_A× SC + P_D×SD)	BC = 1.15(P_A× SC + P_D×SD)	BC = 1.15(P_A× SC + P_D×SD)
SC (Kg/m^3)	a(Dh) + b a = 0.0132ln(H) - 0.0516 b=0.3973	a(Dh) + b a = 0.0133ln(H) - 0.052 b=0.4622	a(Dh) + b a = 0.0145ln(H) - 0.0566 b=0.5516	a(Dh) + b a = 0.0161ln(H) - 0.0628 b=0.6781
SD (m/m^3)	a(Dh)$^{-b}$ a = 0.0192ln(H) + 0.8107 b = 0.09ln(H) + 1.6584	a(Dh)$^{-b}$ a = 0.0208ln(H) + 0.9433 b = 0.096ln(H) + 1.6313	a(Dh)$^{-b}$ a = 0.0268ln(H) + 1.1226 b = 0.097ln(H) + 1.6308	a(Dh)$^{-b}$ a = 0.033ln(H) + 1.3804 b = 0.096ln(H) + 1.6338
B (m)	0.93 (Dh)	0.9 (Dh)	0.84 (Dh)	0.78 (Dh)
S (m)	1.19 (Dh)	1.1 (Dh)	0.96 (Dh)	0.83 (Dh)
T (m)	0.84 (Dh)	0.81 (Dh)	0.75 (Dh)	0.7 (Dh)
J (m)	0.27 (Dh)	0.3 (Dh)	0.3 (Dh)	0.3 (Dh)

Dh: Hole Diameter (in) UCS: Uniaxial Compressive Strength (MPa) BC: Blasting Cost ($/$m^3$)
SC: Specific Charge (Kg/m^3) SD: Specific Drilling (m/m^3) H: Bench height (m)
P_A: Price Anfo ($/Kg) P_D: Price Drilling ($/m)
γ : Angle between plane of bench face and the plane of main joint set

3. Study of previous blasting and choice of a new blasting block

In some previous blasts, the specific charge and specific drilling were high because the technical and economic principles were not observed in the design of the blast pattern, so the results of some blocks were not perfect or ideal. Figure 6 shows a sample of an imperfect blast in the mozonite and quartz monzonite (Trachyte) zone in the Sungun copper mine. In this figure, the continued presence of bulldozer at the side of bench to clear the bottom of bench, a misfire or loose hole, over size, bench toe, ragged crest, and the presence of boulder are clearly visible.

Figure 6. A sample of a previous blast and the destructive events after the blast.

In the Sungun copper mine, two blocks were chosen for blasting. In the first block, the angle between the plane of bench face and the plane of main joint set (γ) is less than 90 degree, and in the second block, this angle is more than 90 degree. According to the rules of the block theory, the angle between the bench face and the main joint set is important. This angle is located between the two normal vectors of the planes. The plane equation according to Equation [2] and the coordinates of normal vector according to Equation [3] are achieved through a dip and dip direction [2].

$$AX + BY + CZ = D \tag{2}$$

$$\begin{aligned} A &= Sin\alpha Sin\beta \\ B &= Sin\alpha Cos\beta \\ C &= Cos\alpha \end{aligned} \tag{3}$$

In Equation [3], α indicates the dip and β represents the dip direction relative to the north. Equation [4] is used to measure the angle between the two planes (γ).

$$\begin{aligned} &P_1(\alpha_1,\beta_1) \rightarrow \hat{n}_1 = (A_1,B_1,C_1) \\ &P_2(\alpha_2,\beta_2) \rightarrow \hat{n}_2 = (A_2,B_2,C_2) \end{aligned} \tag{4}$$

$$\gamma = Cos^{-1}\left(\frac{A_1A_2 + B_1B_2 + C_1C_2}{\sqrt{(A_1^2+B_1^2+C_1^2)(A_2^2+B_2^2+C_2^2)}}\right)$$

For the experimental blocks in the levels of 2200 and 2225 m from the sea level, the dip and dip direction of joint set and the bench face were collected. By considering the Equations [1], [2], and [3], the angles between the main joint plane and the bench face plane in each block were calculated in Tables 10 and 11.

Table 10. Calculation of γ in the level of 2200 m ($\gamma < 90^{\circ}$).

Plate	Description	Amount	A	B	C	γ (Degree)
Main joint	Dip Dip direction	60 135	0.612915	-0.61145	0.5004	16.84
Bench face	Dip Dip direction	70 120	0.814112	-0.46888	0.3426	

Table 11. Calculation of γ in the level of 2225 m ($\gamma > 90^{\circ}$).

Plate	Description	Amount	A	B	C	γ (Degree)
Main joint	Dip Dip direction	60 30	0.432681	0.749885	0.500	103.61
Bench face	Dip Dip direction	70 150	0.47082	-0.81299	0.342	

4. Implementation of operations

Figure 7 is a facade of the experimented blocks in the levels of 2200 and 2225 m. After studying the block considering the joint status and dip style and dip direction of the main joint set, the strength of *in situ* rock by the recorded data in the mine was studied. The selected blocks in the Sungun copper mine, regarding the uniaxial compressive strength, were placed in the third category with a strength between 120 MPa and 180 MPa and according to Tables 8 and 9, the burden, spacing, stemming, and sub-drilling amounts were calculated. The specific charge and specific drilling were anticipated according to the model presented in Tables 8 and 9, considering a bench height of 12.5 m and a hole diameter of 6.5 inches. The results of the calculations are presented in Table 12.

Figure 7. A facade of selected blocks in the levels of 2200 and 2225 m.

Table 12. The selected block features and the calculated pattern in the Sungun copper mine.

Row	Explanation	$\gamma > 90^{\circ}$	$\gamma < 90^{\circ}$
1	Type of rock	Monzonite	Monzonite
2	Strength of rock (MPa)	120-180	120-180
3	Operational level (m)	2225	2200
4	UTM X (Center of block)	7845	7842
5	UTM Y (Center of block)	4632	4966
6	UTM Z (Center of block)	2237.5	2212.5
7	Dip of the main joint set of block	60	60
8	Dip direction of the main joint set of block	30	135
9	Dip of the bench face plate	70	70
10	Dip direction of bench face plate	150	120
11	Main joint set style	$\gamma > 90^{\circ}$	$\gamma < 90^{\circ}$
12	Hole diameter (inch)	6.5	6.5
13	Height of block (m)	12.5	12.5
14	Length of block (m)	80	200
15	Width of block (m)	30	30
16	Burden(m) (rounded)	5.4	5.8
17	Spacing (m) (rounded)	6.2	7.2
18	Stemming(m) (rounded)	5	5
19	sub-drilling(m) (rounded)	2	2
20	Recommended amount of specific charge (kg/m^3)	0.42	0.34
21	Recommended amount of specific drilling (m/m^3)	0.04	0.03

After designing the blast pattern and determining the collars of holes, by survey, the collars were staked out on the blasting site, and then they were drilled by a drill machine with a diameter of 6.5 inches. Figure 8 shows the blasting stages in four sequences.

After blasting, there were no destructive events such as much fly rock and ground vibration. The fragmentation amount and back break in the experimented block were ideal. Figure 9 shows the new and last fragmentation, the lack of back break, and the smooth surface of the bench.

Studying the blasting operation costs in the mine from 2012 to 2014, the average blast cost in monzonite was around US$0.46 for each cubic meter during these 3 years. After carrying out the blasting operation by new methods and by using the models of Tables 8 and 9, it was expected that as well as good technical results, the economical results of blast would be better compared to the previous blasts of mine. Table 8 shows the blasting operation cost for each cubic meter of rock in the Sungun copper mine, trachyte, and monzonite rocks during 2012-2014.

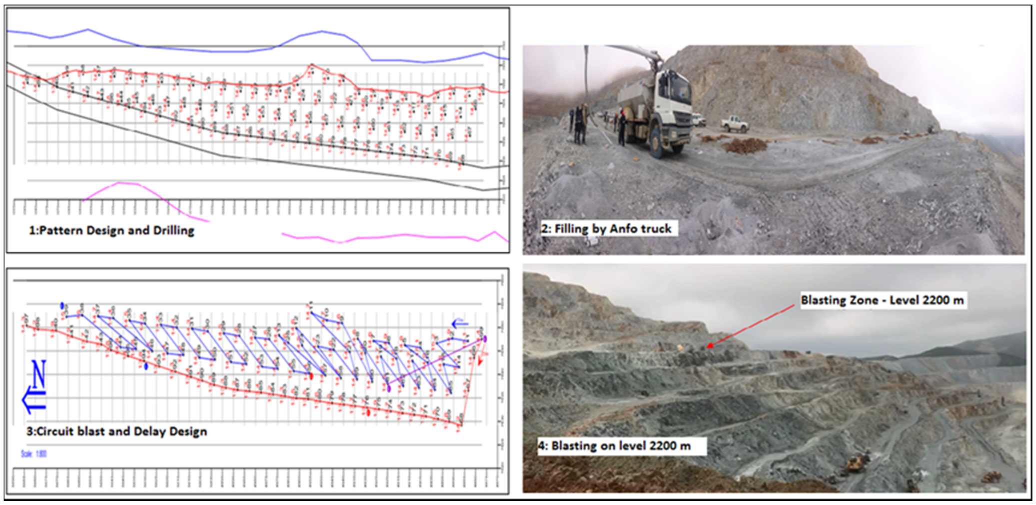

Figure 8. Blasting stages from drilling to the blast in the block in the level of 2200 m.

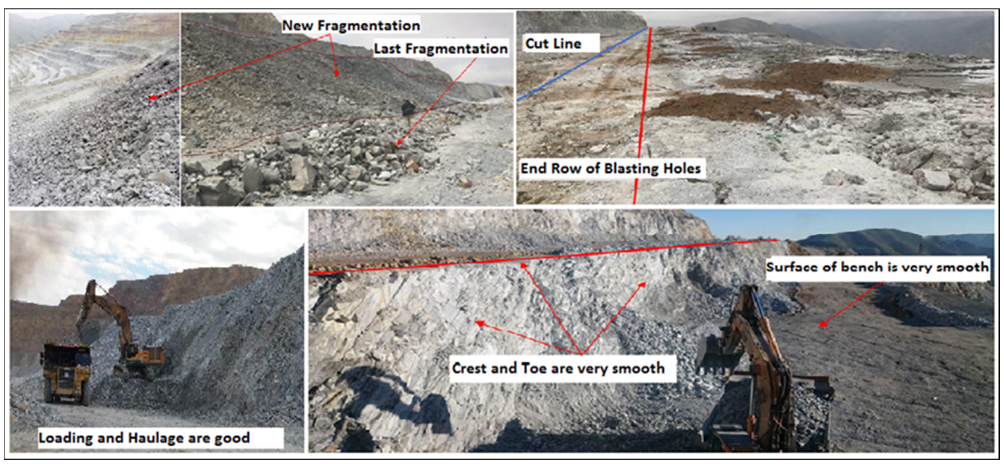

Figure 9. Fragmentation size and the smooth surface after blasting in the level of 2200 m.

Table 13. Blasting operation cost for each cubic meter of rock in the Sungun copper mine.

Year	Type of rock	Blasting cost ($\$/m^3$)	Production volume (m^3)	Total cost of ANFO and drilling ($)	Drilling cost ($)	ANFO cost ($)	Annual total cost of blast ($)
2012	Trachyte	1.072	624,178	622,290.00	220,365.00	401,925.00	669,520.00
2013	Trachyte	1.154	147,914	130,490.83	47,015.00	83,475.83	170,697.50
2014	Trachyte	1.340	315,153	379,668.33	133,800.00	245,868.33	422,423.00
2012	Monzonite	0.450	7,698,287	3,382,903.33	1,178,545.00	2,204,358.33	3,469,284.33
2013	Monzonite	0.473	6,777,431	3,123,798.33	1,090,715.00	2,033,083.33	3,206,296.67
2014	Monzonite	0.479	6,562,884	3,065,720.00	1,063,960.00	2,001,760.00	3,143,351.00

The blasting operation was implemented according to the calculations of Table 12 in the block with the level of 2225 m. γ was more than 90°, and Table 9 was employed to calculate the blast pattern parameters, and the blast results in this block was also acceptable. Figure 10 shows the fragmentation size and bench face condition of the block in the level of 2225 m.

Figure 10. Fragmentation size and the smooth surface after blasting in the level of 2225 m.

5. Blasting results

After carrying out the experimental blasting in the Sungun copper mine, the new results achieved in the experimented blocks were compared with the result of the blasting operations that were implemented some years ago. The results obtained show that the use of the new pattern in this mine has good results compared to with the previous patterns, and the blast operation cost decrease. Table 14 shows a comparison between the old and new patterns.

Table 14. Achieved results of experimental blasting in the Sungun copper mine and its comparison with the previous results.

Row	Explanation	New pattern results	Average of previous state and amount
1	Type of rock	Monzonite	Monzonite
2	Strength of rock (MPa)	120-180	120-180
3	bench height (m)	12.5	12.5
4	Average of burden (m)	5.8	5.1
5	Average of spacing (m)	7.2	6
6	Average of stemming (m)	5	3
7	Average of sub-drilling (m)	2	1.3
8	Anticipated amount of specific charge (kg/m^3)	0.34	Predictive methods were not used
9	Anticipated amount of specific drilling (m/m^3)	0.03	Predictive methods were not used
10	Fly rock	Under 10 m	Too much
11	Ground vibration	Standard (in standard range)	Strongly
12	Loading and dilution	Suitable for loading system and without dilution	Distributed and diluted
13	Air blast	It doesn't have	It has (for the lack of perfect stemming)
14	Back break	To 1 m	To 6 m
15	Style &amount of rock fragmentation	Size is nearly 0 to 40 cm	Around 30% of block volume has been more than 1.5 m
16	Bench toe	Most bench toe is smooth	Too much
17	Bulldozer program	On the last day, block survey is used to clean up	It has been completely in block in loading duration
18	Using hammer	It doesn't have	It has
19	Average amount of real specific charge (kg/m^3)	0.31	0.36
20	Average amount of real specific drilling (m/m^3)	0.027	0.03
21	Average of annual blast cost (US$/$m^3$)	0.441	0.46
22	Discrepancy between new specific charge and average of the old one (kg/m^3)	0.05	
23	Discrepancy between new specific drilling and average of the old one (m/m^3)	0.003	
24	Discrepancy between blasting operation cost and average of the old one (US$/$m^3$)	0.02	
25	Saving money for the blasting pattern done according to the recommended pattern and with calculation of 7.5 million m³ volume of stripping & extraction (US$1000)	150	

By applying the new model, the amount of US$150,000 was saved by reducing the ANFO consumption, reducing the drilling meters, and reducing the costs of lateral blasting operations. If the working hours of Bulldozer and Hammer is reduced by taking this new approach, the savings resulting from the use of the new model will be much higher.

6. Conclusions

Applying a new model for calculation of burden, spacing, stemming and sub-drilling as well as anticipation of the specific charge and specific drilling that were presented in this work can decrease the destructive events of blast such as weak fragmentation, ground vibration, fly rock, bench toe and back break, consumed explosive material and drilling meters of the blast hole. Also we can predict the specific charge and specific drilling using the above mentioned model. In this work, the presented new model regarding hole diameter, uniaxial compressive strength (UCS), and bench height as well as the main joint set plane status were experimented by a field survey in the Sungun copper mine, and the results of the blast operation were satisfactory. In this work, the block theory and joint set studies and UCS in the model were considered. With this simple model, the specific charge and specific drilling are done quickly using several available parameters. In this model, the linear relationship (SC = a(Dh) + b) between the hole diameter and the specific charge and the exponential relationship ($SD = a(Dh)^{-b}$) between the hole diameter and the specific drilling were determined. One of the most important relationships extracted in this work is the calculation of the blasting cost ($BC = 1.15\ (P_A \times SC + P_D \times SD)$), which can be easily calculated using the specific charge and specific drilling. On the other hand, in this work, the specific charge and specific drilling were studied during the years 2012-2014 in the Sungun copper mine, and they were compared with the specific charge and specific drilling that was the result of blast. The difference between the specific charge and specific drilling were, respectively, 0.05 kg/m^3 and 0.003 m/m^3, which led to a difference in cost of US$0.02 per m^3 compared with the previous blasts. With this model for a blasting pattern design, in addition to the proper blasting, the blasting cost was also reduced. The result of the new model in this mine, in addition to reducing the destructive effects after the blast, was estimated at US$150,000 per year according to the 7.5 million cubic meters volume of the blasting per year.

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ارائه یک مدل فنی و اقتصادی جدید جهت محاسبه خرج ویژه و حفاری ویژه با استفاده از قطر چال، ارتفاع پله، مقاومت فشاری تک محوره و جهت دسته درزه

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چکیده:

محاسبه خرج ویژه و حفاری ویژه قبل از انجام عملیات انفجار نقش مهمی در طراحی الگوهای انفجار و کاهش قیمت تمام شده ماده معدنی دارد. در این تحقیق اطلاعات حفاری و انفجار معادن مس سونگون، میدوک و چاه فیروزه در ایران جمع آوری گردید و رابطه و مدلی بین خرج ویژه و حفاری ویژه با قطر چال، ارتفاع پله، مقاومت تک محوره سنگ و جهت دسته درزه اصلی بلوک انفجاری بدست آمد. پس از بدست آوردن مدل فنی و اقتصادی فوق جهت محاسبه خرج ویژه و حفاری ویژه، این مدل در معدن مس سونگون آزمایش گردید. به دلیل عدم توجه کافی در طراحی الگوی انفجارهای قبلی این معدن و به دلیل سختی بالای سنگ ها در برخی از قسمت های معدن، پدیده‌های مخرب پس از انفجار مانند قطعات بزرگ سنگ، عقب زدگی، پاشنه، خرج ویژه و حفاری ویژه بالا، پرتاب سنگ و لرزش زمین مشاهده گردیده که پس از بکارگیری از این مدل فنی و اقتصادی جدید این پدیده های مخرب به حداقل ممکن رسید. خرج ویژه و حفاری ویژه بعنوان مهمترین پارامترهای فنی و اقتصادی در طراحی الگوی انفجار بوده و نقش مهمی در کاهش هزینه انفجار دارند. هزینه انفجار می تواند تا حد زیادی با بررسی دقیق و محاسبه این پارامترها کنترل شود. با افزایش مقاومت سنگ و زاویه بین سطح سینه کار و صفحه دسته درزه اصلی پله، خرج ویژه و حفاری ویژه افزایش می‌یابد. از طرف دیگر، وقتی قطر چال در بازه مقاومت سنگ افزایش یابد، خرج ویژه و حفاری ویژه کاهش می‌یابد.

کلمات کلیدی: خرج ویژه و حفاری ویژه، قطر چال، ارتفاع پله، مقاومت تک محوره، جهت دسته درزه.