PROSPECTS OF THE USE OF GRAIN-SIZE COMPOSITION PREDICTING MODELS AFTER EXPLOSION IN OPEN-PIT MINING

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Abstract

Mineral resources are the basis of economic growth and independence of any state. Various technologies and methods are used for the mineral extraction. However, the drilling and blasting operations are still dominant. Drilling and blasting operations are first in the chain of mining technological process and determine the economic efficiency of the entire cycle of mining and primary processing of minerals in the enterprise. The cost of drilling and blasting operations is a significant part of total production costs of large mining companies. Therefore, the improvement of the drilling and blasting technology is one of the key issues in the complex of tasks of the deposit development efficiency improvement. In this context, one of the main technological tasks facing mining engineers today is a reduction of the oversized fraction output. Currently, the efforts of scientists are aimed at developing reliable grain-size composition predicting models for the extracting rock mass, as one of the initial factors for reducing economic losses throughout the technological cycle. However, many of the existing models do not consider the mutual influence of a number of factors, which explains the instability of the drilling and blasting performance indicators, their low efficiency and, as a result, an increased oversized fraction output. The model for grain-size composition predicting for mining enterprises will be interesting only if the proposed technological solution together with a pre-established fraction of rock mass will increase the efficiency of blasting operations with the desired reduction of all material and non-material expenditures. In this paper the authors give a brief overview of the global mining volumes; provides information on the extraction of key types of minerals (mineral fuel, ferrous metals, non-ferrous metals, precious metals, industrial minerals), as well as revenues derived from their sale. On the example of domestic companies, the authors give the analysis of approaches to solving the issues of predicting of the oversized fraction output after the explosion. They also specify the direction for future actions in creating a predicting model for the rock mass output of a certain fragmentation after the explosion.

Keywords: rock destruction, blasting, economics, mineral resources, grain-size composition, fragmentation

1 INTRODUCTION

Currently, the volume of proved solid minerals reserves is large enough, which is a good basis for creating a well-functioning economy of the country. In this regard, a detailed and objective analysis of the situation, in the context of the analysis of global trends in the development of the mining industry, is crucial to determine the potential risks in the development of the deposit.

A promising development strategy of a mining enterprise directly depends on the complexity of extracting a component from the subsoil (the impact of mining, geological and technical factors), as well as from the cost of extracted raw materials on the market. However, there are also indirect geopolitical factors leading to a shortage of mineral resources.

Thus, detailed knowledge of the mining volume and certain competencies in the economic sector are important for strategic decision making. The reason is that changes in the mineral resource market can significantly affect the welfare of the company, industry or even the country in general.

Figure 1 shows the change in the mining volumes from 1984 to 2015 by key regions [14].

Analysis of the graph shows that more than half of the raw materials is currently mined in the Asian region (57.58%), followed by North America, Europe, Latin America, Oceania and Africa (Table 1). Whereas the total mining volume for this period almost doubled, the percentage ratio by regions stayed almost the same.

Based on the above mentioned, it can be predicted that consumption volumes will grow, companies will switch to developing deposits with a poorer raw material base, which will inevitably lead to an increase in production expenditures.

The power balance in the near future will remain unchanged. Companies, regions, and countries with technological advantage ensuring the minimization of costs at each specific process or operation will be successful.

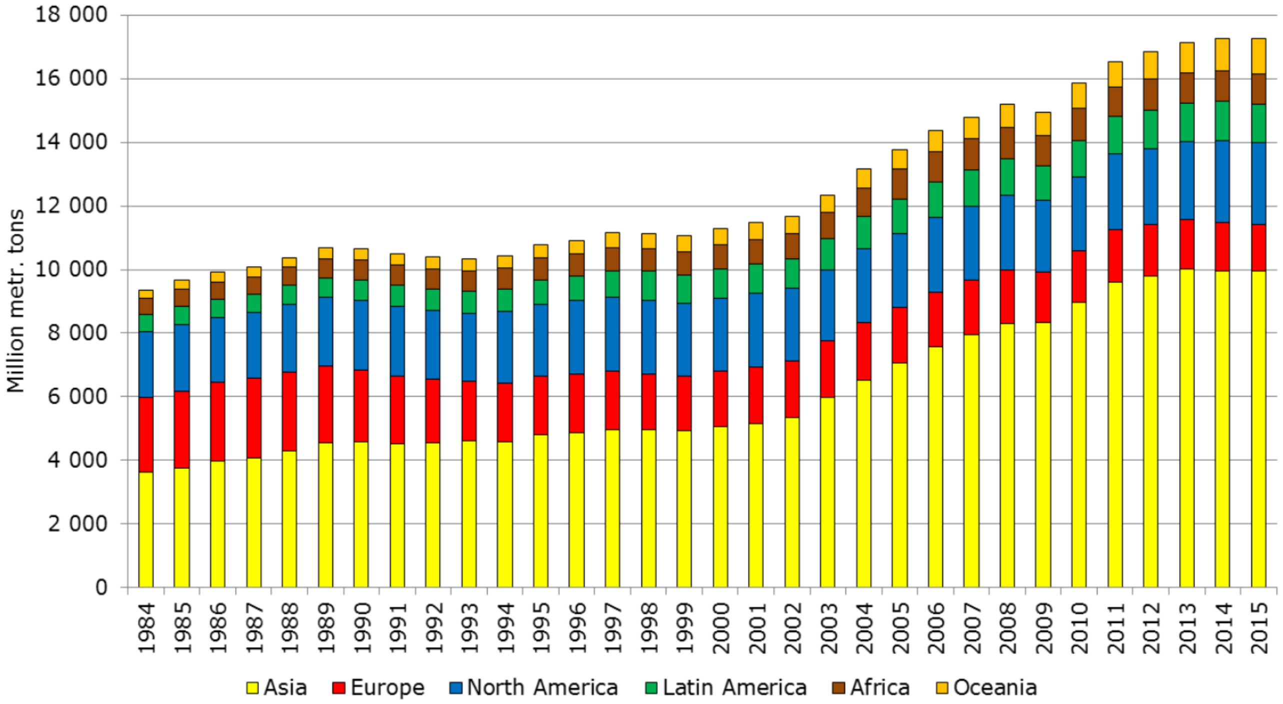


Figure 1. Global mineral resources mining volumes

Table 1. Mineral resources mining volumes by regions in 2015

Region	Mining volume, tons	Percentage ratio, %	Increment rate from 1984, %
Africa	933 400 198	5.40	52.63
Asia	9 943 982 008	57.58	36.50
Europe	1 481 935 544	8.58	158.19
Latin America	1 207 621 082	6.99	46.93
North America	2 568 568 853	14.87	80.19
Oceania	1 134 181 099	6.56	22.42
Total	17 269 688 784	100	54.12

Figures 2 and 3 show countries with highest mineral extraction volumes and revenue in their regions [14].

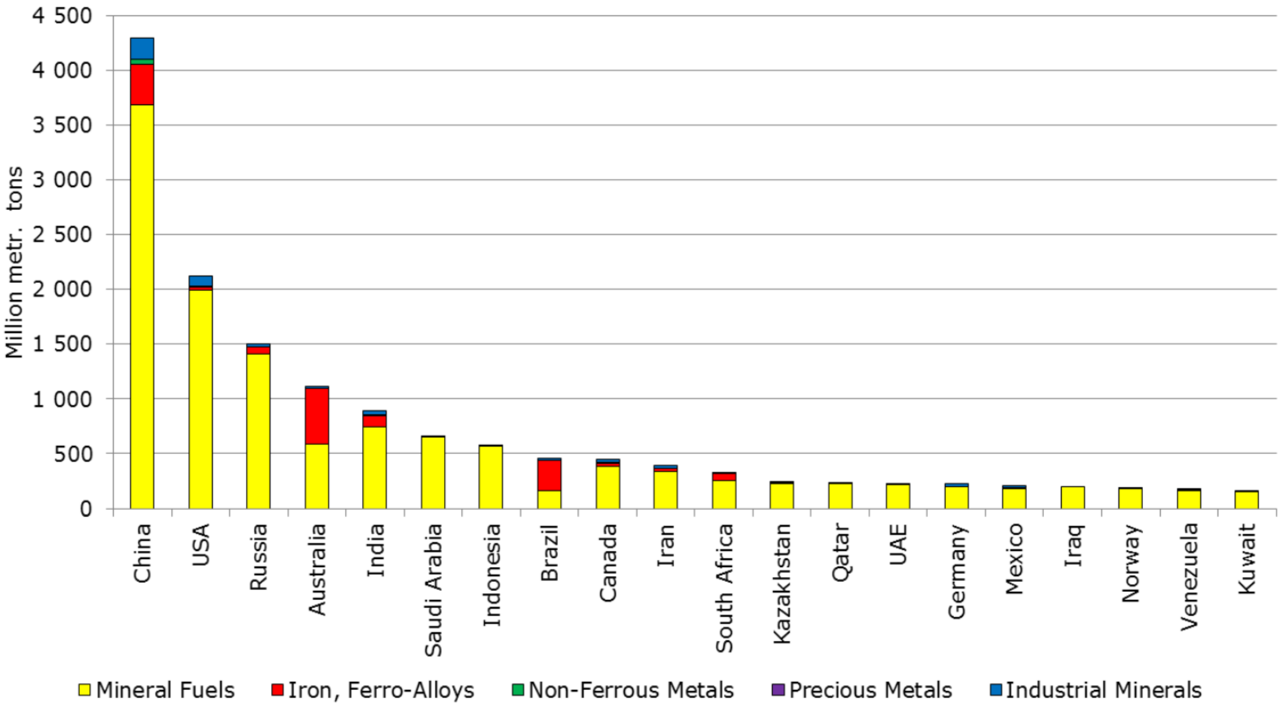


Figure 2. Leaders in mineral extraction volumes

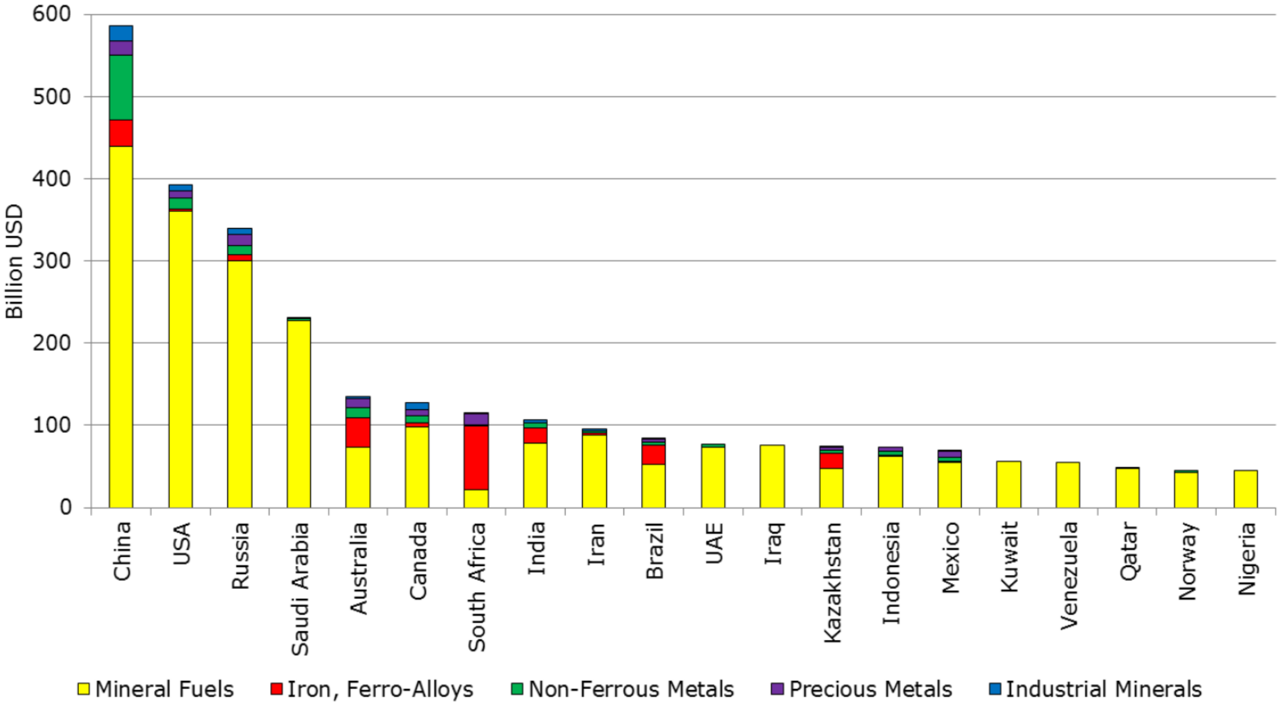


Figure 3. Leaders in financial revenue from the sale of raw materials

Rock mass shattering is initial in the technological chain of a production process, the efficiency of which largely determines the productivity of the loading, delivery and transport equipment, and also indirectly affects the loss and dilution of ore. The efficiency of ore blasting fragmentation also affects directly the costs of its mechanical fragmentation during processing.

With an increase in the volume of blasting operations, there is often an increase in the output of the oversized fraction, due to the deterioration of mining and geological conditions as the depth of mining increases, the incorrect choice of drilling and blasting parameters caused by the desire to reduce production costs, etc. This phenomenon arises an uncontrolled increase in additional costs of secondary operations, which in general, negatively affects the economic efficiency of the company.

In this connection, it is very important to solve the problem of predicting the output of the grain-size composition of the mining rock mass at the designing stage, based on the available mining, geological and technical data.

2 METHODS

2.1 Current condition and prospects of mineral resources extraction by world leaders

As of 2015, the world top three in the mineral extraction volumes and the sales revenue includes China, the United States, and Russia (Table 2).

Table 2. Mineral extraction volumes and the funds raised from their sale

Mineral resources	**Extraction volume, tons**			**Funds raised, mln $**		
	Russia	**USA**	**China**	**Russia**	**USA**	**China**
Mineral fuels	1 413 954 902	1 992 547 281	3 682 421 706	299 936	359 860	439 113
Ferrous metals	56 242 436	29 258 360	375 226 780	8 492	2 751	31 725
Non-ferrous metals	4 678 909	4 164 472	40 608 339	10 794	12 559	79 091
Precious metals	1 925	1 319	3 843	12 771	8 873	18 496
Industrials minerals	30 495 188	92 521 000	195 685 100	7 142	8 112	18 495
Total	1 505 373 360	2 118 492 432	4 293 945 768	339 135	392 155	586 920

Open-pit mining is the most popular mineral extraction method. It entails a lot of technological and environmental problems [4, 8, 10]. One of the primary technological tasks for open-pit mining is the reduction of the oversized fraction output.

As mentioned above, the quality of blasting operations directly affects the efficiency of rock mass fragmentation. It leads mainly to a significant increase in the costs of mechanical fragmentation and grinding of ore, which are the most energy-consuming processes in mining and processing.

The share of breakage costs, depending on the strength of rocks, is 20-35%. Factors that predetermine the growth of these costs are:

– reduction in the ore mass output from 1 linear meter of the well;

– an increase in the consumption of explosive materials per ton of broken ore;

– a decrease in the productivity of drilling equipment (in meters of drilling or in cubic meters of a drilled mountain massif).

It should also be noted that each company makes its own requirements for the conditioning fraction (conditioning piece), and, as a consequence, for the size of a fraction considered oversized. This value is influenced by the following factors: the type of mining and crushing equipment used, the explosives used, the type and physicomechanical properties of the extracted mineral resources, etc.

The standard value of the oversized output is determined at the stage of the work execution plan development and usually varies in the range of 1-5%.

Currently there is a large number of methods for determining and predicting the fragmentation of broken rock massif [3, 6, 7, 9, 15, 16], but there is no integrated scientifically proven design model for determining drilling and blasting operations parameters and taking into account the set of factors influencing the results of explosive breakage.

Let us compare the results of calculations of the average piece size the of the mined rock of several different prediction models, depending on the parameters included in the model.

2.2 Kuznetsov's model [6]

In 1973 a Soviet scientist Vitaly Kuznetsov revealed an expression that allows us to determine the average size of the blast rock mass. The author defined the form of his expression using regression analysis.

A general form of the Kuznetsov's expression:

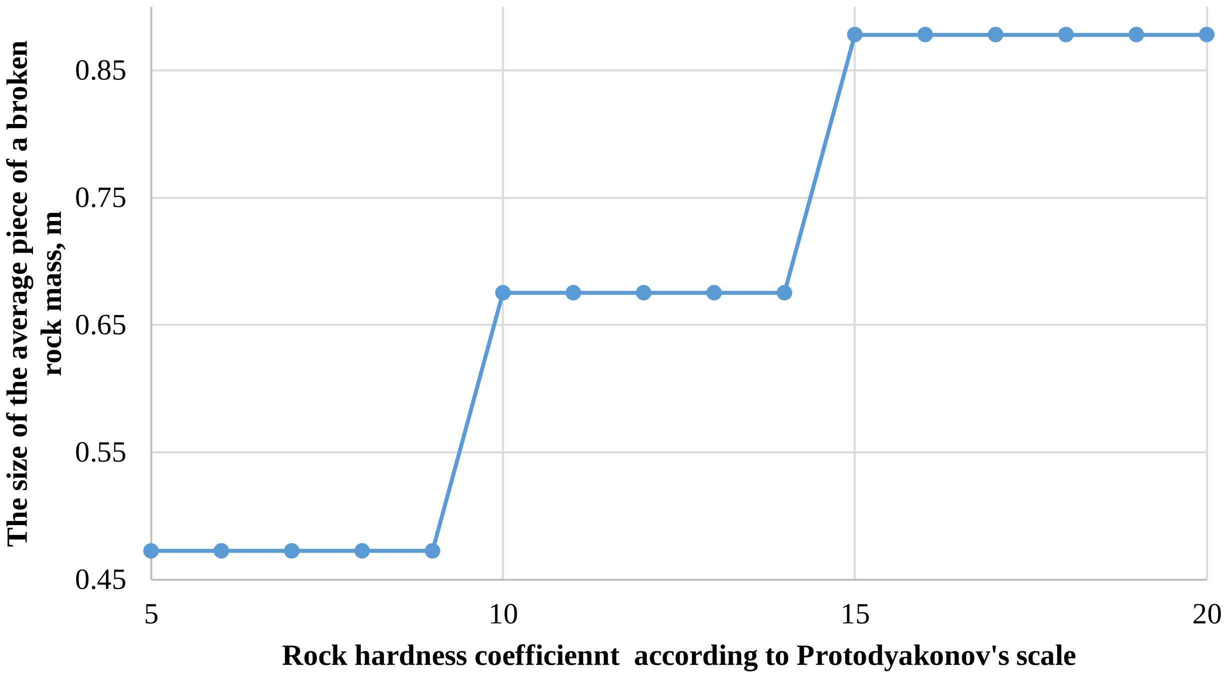
$$\bar{x} = A \cdot \left(\frac{V_0}{Q} \right)^{\frac{4}{5}} \cdot Q^{\frac{1}{6}}, \text{ cm}, \tag{1}$$

where $A = \begin{cases} 7 - for\ medium\ hard\ rock\ (f = 8 - 10) \\ 10 - for\ hard, but\ fractured\ rock\ (f = 10 - 14) \\ 13 - for\ very\ hard\ and\ poorly\ fractured\ rock\ (f = 12 - 16) \end{cases}$;

V_0 – rock mass volume, m^3; Q – explosive mass in the well, kg.

When analyzing the results of calculations using this method of determining the average size of the blast rock mass, we determined the main dependencies of the change in the average piece size of the blast rock mass from the rock hardness, rock volume and the mass of explosives in the well (Fig. 4, a-c).

a)



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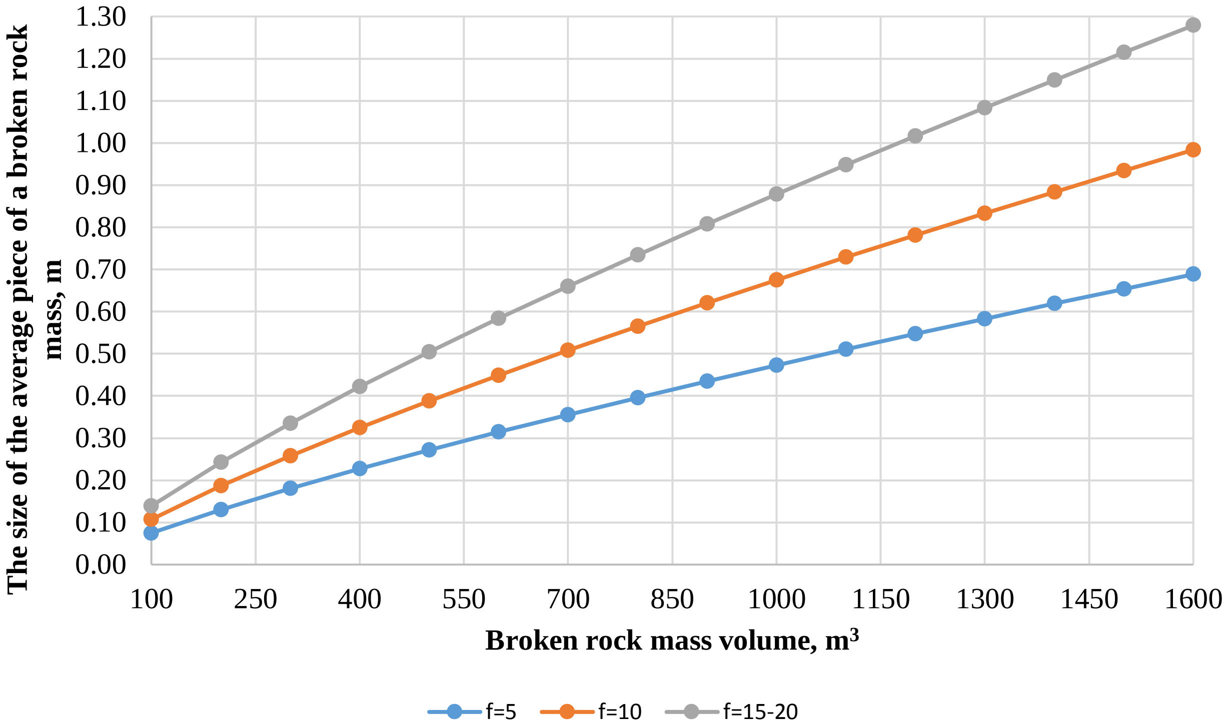

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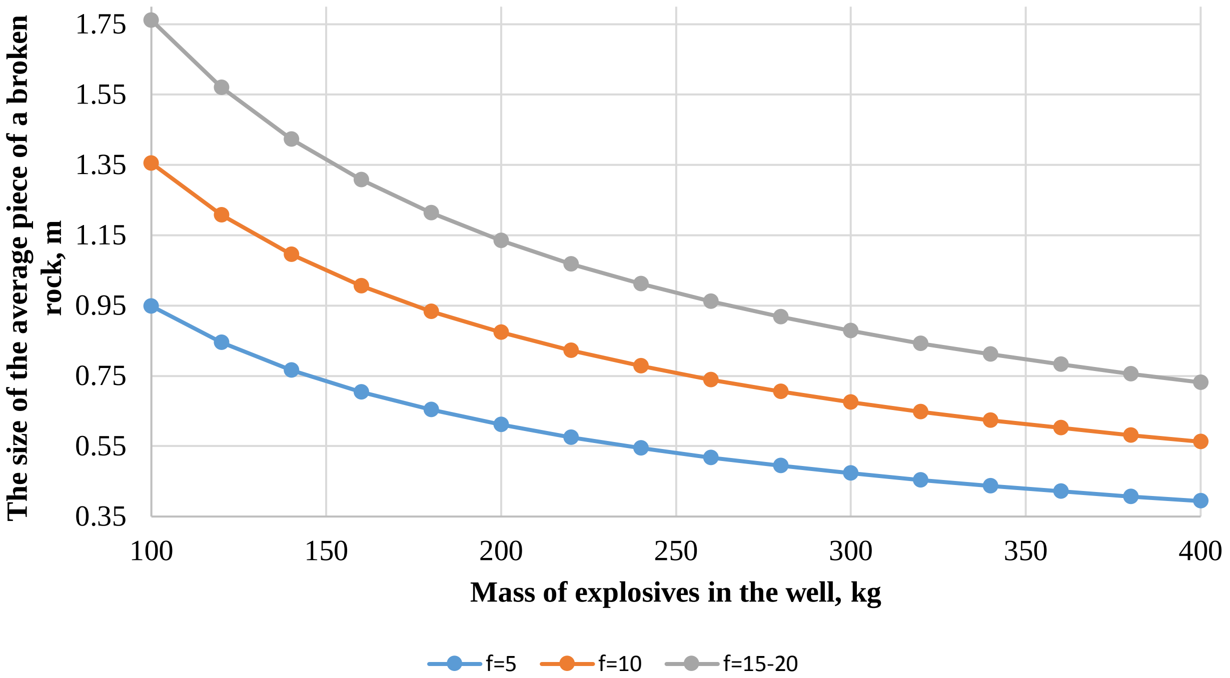


Figure 4. Dependences of the average piece size of a broken rock mass from various factors:
a) rock hardness; b) volume of broken rock mass; c) explosive mass in the well

The graph (Fig. 4, a) shows the curve of the change in the average broken rock mass size from the rock hardness. While in the proposed Kuznetsov's model the rock hardness is denoted by a coefficient that combines the rock hardness ranges (Formula 1), the dependency graph has a step-like appearance, which proves an indirect impact of this indicator on the final value of the required average broken rock mass size.

Figure 4, b shows the dependence of the change in the average broken rock mass from the volume of the blasting rock mass under different rock hardness. It follows from the graph that when the explosive is equal 300 kg, and the hardness coefficient f = 15-20, the explosion energy should be sufficient to destroy ≈1000 m3 of a rock mass, the size class being ≈0.9 m. According to calculations under the same conditions, but with rock hardness f = 10, broken 1000 m3 should have a fraction of ≈0.7 m, and for f = 5 - 0.5 m.

The graph (Fig. 4, c) shows the dependence of the change in the average broken rock mass from the total amount of explosive in the well at different ranges of the rock hardness. From the graph, it follows that for breaking 1000 m3 of rock mass with a coefficient of hardness f = 15-20 and a size of 0.9 m, it is necessary to have about 300 kg of explosive. At f = 10, the explosive mass will be 180-200 kg, and at f = 5 – 100-120 kg.

2.3 KUZ-RAM model [3]

The English researcher Cunningham made a significant contribution to the development of the study of rock fragmentation from blasting. He proposed using the Rosin-Rammler curve to describe the grain-size composition of the blasted rock. In particular, he combined the expression of Kuznetsov and the Rosin-Rammler curve, this is why the model was named "Kuz-Ram Model".

Kuz-Ram model is the most used model for predicting rock fragmentation from blasting. This model consists of the following basic equations:

- expression of Vitaly Kuznetsov;
- expression of Rosin-Rammler;
- expression of uniformity index.

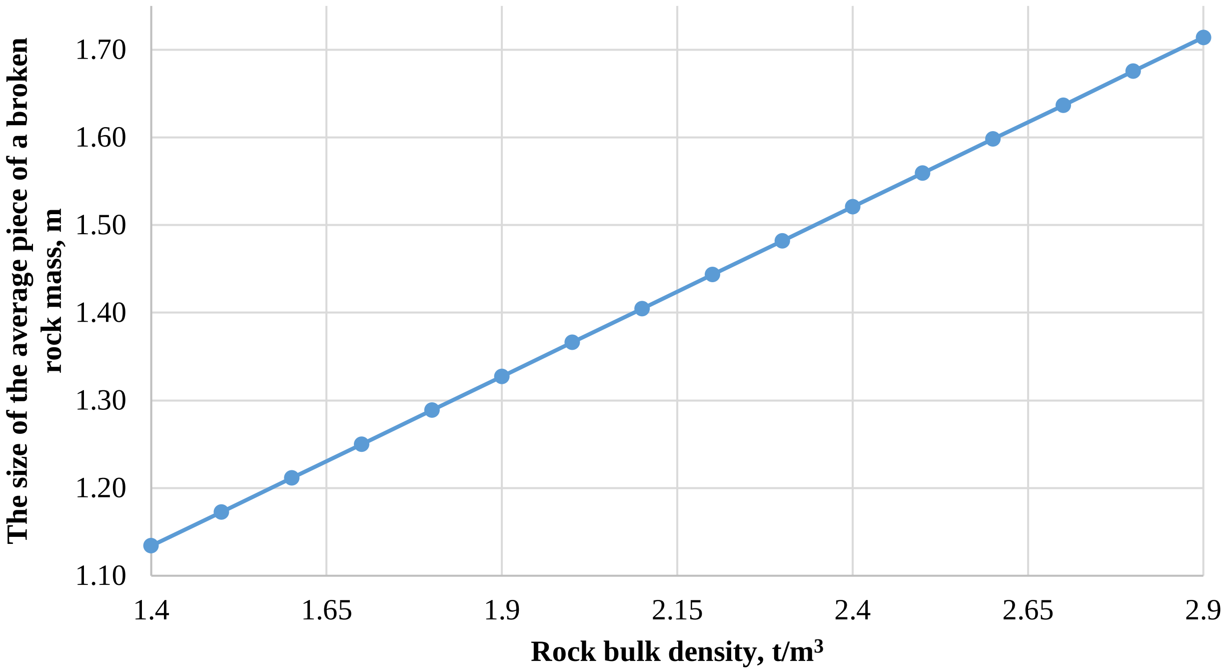
The Cunningham equation is:

$$\bar{x} = AK^{-0.8} \cdot Q^{\frac{1}{6}} \cdot \left(\frac{115}{RWS}\right)^{\frac{19}{30}}, \text{ cm}, \quad (2)$$

where A is a rock factor; K – specific consumption of explosive, kg/m^3; Q – explosive mass in the well, kg; RWS –the relative equivalent of explosives according to the heat of explosion in relation to the ANFO; *115* – RWS of trinitrotoluene.

Analysis of the results of calculations based on this method showed the main dependences of the change in the average piece of the broken rock mass from the bulk density of the rock, explosives specific consumption and the mass of explosives in the well (Fig. 5, a-c).

a)



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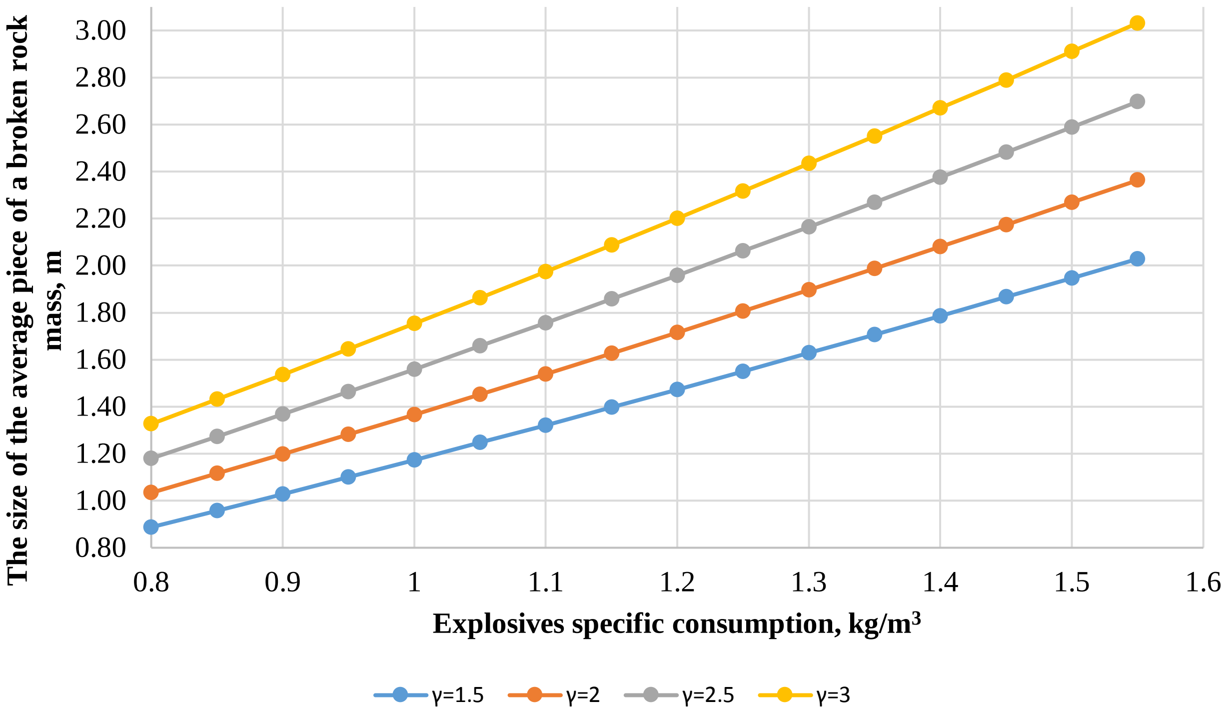

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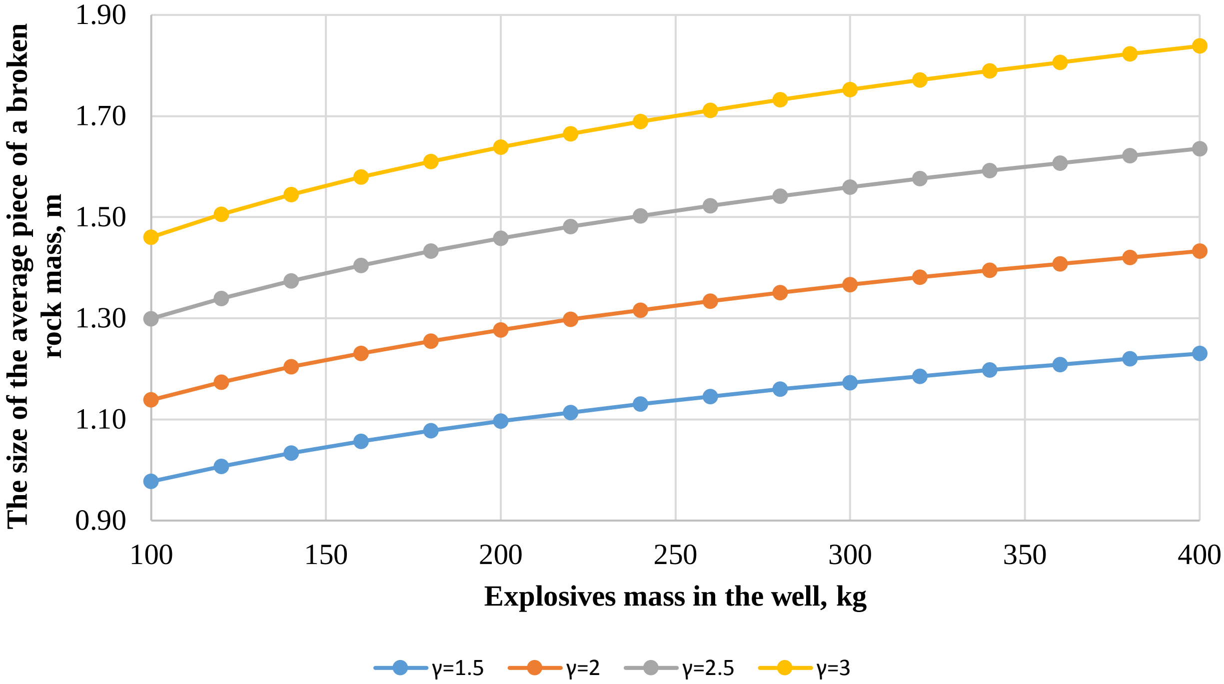


Figure 5. Dependences of the change in the size of the average broken rock mass from various factors: a) rock bulk density; b) explosive specific consumption; c) explosives mass in the well

The dependence of the change in the average broken rock mass size on the bulk rock density is shown in Figure 5, a. The graph is a linear relationship.

Since this calculation model represents the coefficient of rock hardness (*A*) by the process of calculating several formulas, and does not represent the indicator in the form of a hardness scale in the range from 1 to 25 familiar to domestic researchers, but shows a certain numerical value, the subsequent dependences will be considered when changing the rock bulk density.

The graph (Fig. 5, b) shows the dependence of the change in the average broken rock mass on the specific consumption of the explosive at different numerical values of the rock bulk density. This dependence is constructed for the pillar (*RMD = 50*). From the graph it follows that with an average specific explosive consumption of 1.0 kg / m3 and with a bulk rock density of γ = 1.5 t / m3, the size of the broken rock mass will be ≈1.2 m, with γ = 2.0 t / m3 - 1.4 m, at γ = 2.5 t / m3 - 1.5-1.6 m and at γ = 3.0 t / m3 - 1.7-1.8 m.

The graph (Fig. 5, c) shows the dependence of the change in the average broken rock mass size from the mass of explosives in the well at various numerical values of the rock bulk density. As shown in Figure 3, when the specified amount of rock mass with a bulk density of rock is γ = 1.5 t / m3 and the mass of explosives in the well is 300 kg, the predicted size of the broken rock mass will be ≈1.2 m, with γ = 2.0 t / m3 - 1.4 m, at γ = 2.5 t / m3 - 1.5-1.6 m and at γ = 3.0 t / m3 - 1.7-1.8 m.

2.4 KCO model [12]

This model is an extended version of the Kuz-Ram model. In this model, the Rosin-Rammler function, used to describe the fragmentation curve, is replaced by the function "Swebrec".

The Swebrec function includes 3 basic parameters:

– the maximum size (x_{max});
– grinding class (x_{50});
– the degree of waviness of the curve (b).

The Swebrec function is defined as:

$$P(x) = \frac{1}{\left(1 + \left(\frac{\ln(x)}{\ln \frac{x_{max}}{x_{50}}}\right)^b\right)}, \%, \quad (3)$$

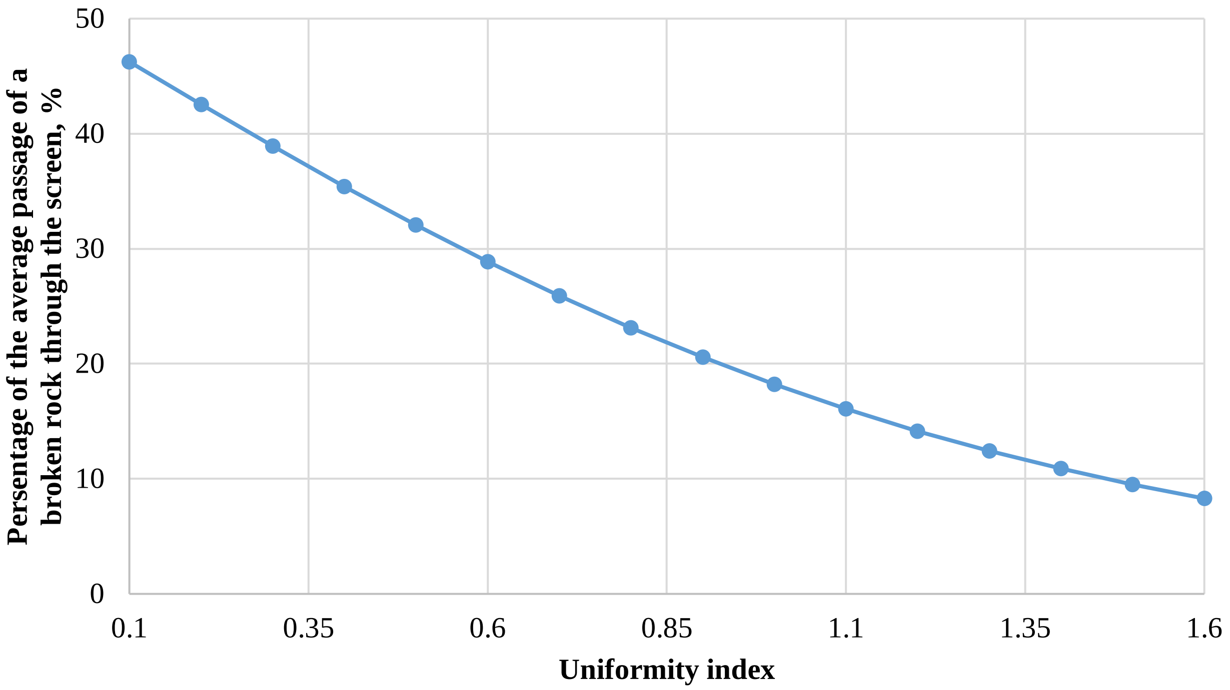
where *P(x)* – is the percentage of material passing through the size of the sieve x, %; *b* is the degree of the corrugation of the curve.

The model was called Kuznetsov-Cunningham-Ouchterlony (Kuznetsov-Cunningham-Ouchterlony) - KCO.

This model does not predict the output of a certain fraction after the explosion (i.g., the numerical index of the average piece of broken rock mass), but calculates the percentage of the broken rock mass passing through the screen.

When analyzing the results of calculations the main dependencies were established on the uniformity index and 50% passage through the screen (Figure 6, a, b).

a)



b)

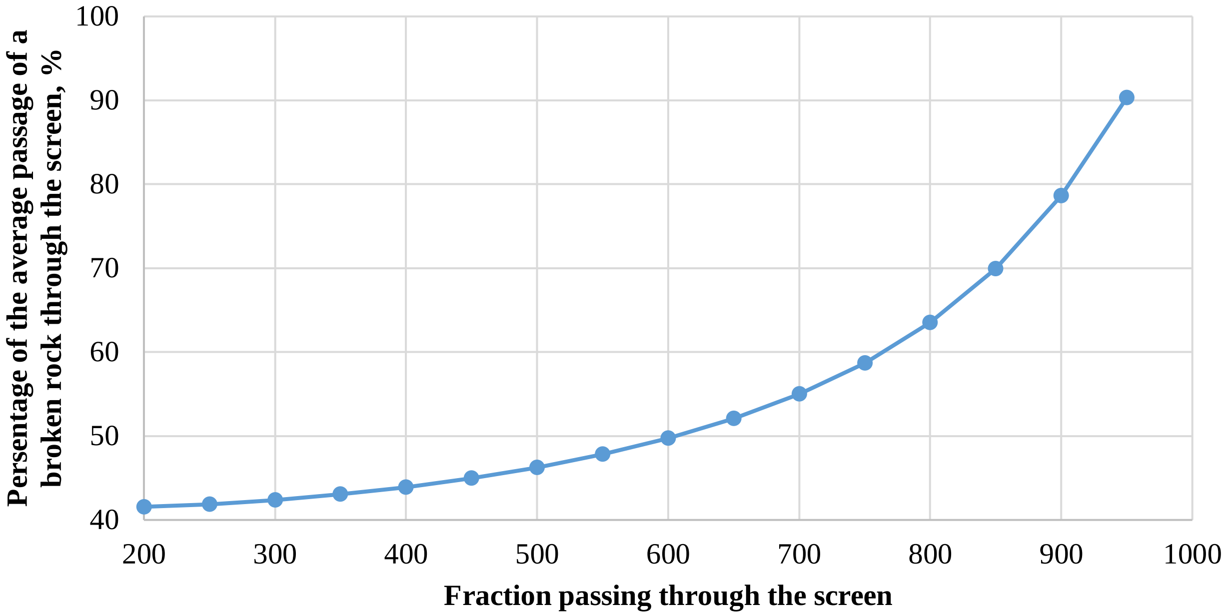


Figure 6. Dependences of the change in the size of the average broken rock mass from various factors: a) uniformity index; b) maximum fraction of the screen

The graph (Fig. 6, a) shows the dependence of the change in the passage of an average broken rock mass through the screen from the uniformity index. With an increase in the uniformity index, the passage of the broken rock mass through the screen is reduced. With a maximum sieve size of 1000 mm, the percentage of passage through the screen varies from 8 to 46%.

The graph (Fig. 6, b) shows the dependence of the change in the passage of an average broken rock mass through the screen from the maximum fraction passing to the screen. With a maximum screen size of 1000 mm, increasing the possibility of passing a certain fraction from 200 to 950 mm, we get the indicated dependence. The percentage of passage through the screen varies from 42 to 90% (depending on the largest fraction that can pass through the screen).

3 RESULTS

As a result of the considered models' analysis, the following conclusions were made.

Summarizing the results of the analysis of calculations performed by the Kuznetsov's model it can be concluded that this model does not take into account the type of explosives used, the parameters of the explosive network and the physical and mechanical properties of rocks (except for the hardness). Therefore, this model can be used only for large-scale calculations or when having large statistical material for each specific enterprise.

Analysis of the Kuz-Ram model let us conclude that the available initial data is sufficient enough to accurately predict rock piece fragmentation after the explosion. Working with this model allows including the predicted fragmentation rates as a percentage, and therefore it is possible to predict the percentage of a certain fraction after the blasting. This model is widely used and improved by many scientists around the world, which indicates its flexibility.

KCO model and other similar models are recommended for use in addition to models capable of calculating the fraction of the mined rock mass in advance. Such integration of models will allow the mining enterprise to predict possible problems with fragmentation.

Thus, the authors of the article briefly presented some factors influencing the calculation of the value of the average broken rock mass.

In the presented models the mutual influence of factors is mostly neglected, which explains the instability of drilling and blasting operations indicators, their low efficiency and, as a consequence, an increased output of oversized fractions. Therefore, it is being discussed massively to analyze and develop techniques capable of predicting the grain-size composition of the broken rock mass as one of the initial factors for reducing economic losses in the technological cycle.

4 DISCUSSION

In general, the parameters that can affect the results of rock mass fragmentation can be divided into two main groups - controlled and uncontrolled, and four subgroups (Table 3) [1, 2, 5, 11].

Table 3. Classification of parameters affecting the rock mass fragmentation

Controlled parameters		**Uncontrolled parameters**	
Parameters of drilling and blasting operations	**Parameters of explosives**	**Rock mass characteristics**	**Geomechanics characteristics of undisturbed rock mass**
A line of least resistance	Explosive type	Fracturing	Rock mass type
Distance between wells	Explosive density	Blocky structure	Density
Chamber height	Explosive power	Number of fracture systems	Hardness
A diameter of the well	Specific mass of explosive	A distance between the fractures and orientation	Resistance and plasticity
A depth of the well	Capacity rate	Fracture size	Porosity and permeability
Stemming size	Detonation velocity	Intensity of fracturing	Mineral composition and grain size
Sub-drill size	Blasting energy per unit mass	Explosive coefficient	Characteristics of weathering
A tilt angle of well			Presence of watering
Charge value			Compressive strength
Number of deceleration steps			Tensile strength
Number of rows in blasting wells			Shear strength
			Cohesive strength
			Elastic modulus
			Poisson's ratio

Currently, the dependence of the average broken rock piece on the parameters of drilling and blasting operations and rock properties is determined for each mining enterprise by empirical patterns based on the experience of analogical enterprises, and its rational values at the operating enterprise - by conducting a series of pilot explosions.

The review of existing methods for determining a broken rock mass fragmentation showed that today there is no single scientifically proven policy for determining this parameter. Usually, the proposed methods do not take into account the interaction of a number of factors, such as the physical and mechanical properties of the mass, the type of explosive used, the diameter of the charge, the charge construction, the charge initiation site, the charge length and the undercharge value, the length and quality of the tamping, and the interaction of simultaneously exploded charges. It explains the instability of the parameters of drilling and blasting operations, their low efficiency and, as a result, an increased output of oversized fractures.

Therefore, the scientific community is widely developing both a technologically and economically efficient method for fragmenting of an oversized fraction and a methodology for shattering parameters that allow reducing the specific consumption of an explosive and increasing the safety of blasting operations.

5 CONCLUSION

Improvement of drilling and blasting operations is one of the ways to increase the efficiency of field development. Depending on the correctness of the drilling and blasting operation parameters calculation, the technical and economic performance of the block can significantly change [17].

From the above mentioned, it can be concluded that production volumes are steadily growing, at the same time the demand for the creation of more powerful explosives and the development of new prediction models (techniques) or models determining the grain-size composition of the rock mass is also increasing.

When implementing the internal development strategy, enterprises should regularly analyze the technical and economic performance indicators. The analysis should change the orientation of the economic policy from the predominantly costly to resource-saving and environmentally safe.

It is necessary to study a large number of models predicting the grain-size composition output of the rock mass, which will provide more details about the main factors influencing the results of the explosion. The efficiency of such analysis depends not only on the improved methods but also on the analysis immediacy. Current science and technology development rates demand promptly production change. Hence the main requirements of the analysis are its consistency, complexity, and immediacy [13].

Acknowledgments

Work is conducted within the framework of the grant of the President of the Russian Federation for state support of young Russian scientists - candidates of science (MK-1178.2018.8).

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