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A method of estimating the contents of components, structural and physical-mechanical properties of rocks

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Abstract. The method for estimation of the mean value and the mode of the property becomes important with increasing the depth growth of mining operations and the complexity degree of excavation sites, the growth of number of cases, when geological information volume representing the level of values of structural and physical-mechanical properties is insufficient. The reliability of estimates is achieved through the involvement of different characteristics of the studied property. The developed method is based on calculation of prediction estimates of the mean value and the mode, which allow providing the accuracy of the estimates with incomplete information, and when the type of the studied property distribution is unknown.

1. Introduction

The efficiency of preliminary surveying of deposit reserves, drilling and blasting, loading and unloading operations, ore extraction and separation depends on certainty and accuracy of methods for assessment, determination and forecasting of not only contents of components, but also values of structural, physical and mechanical properties of rocks. Yield of boulders and fine grinded blasted mined rocks leads to the increase of expenses for extraction, losses and clogging of ore, and to the decrease of the production capacity [1, 2]. Well-known traditional arithmetic mean and weighted mean methods for determination of mean metal content values, structural, physical and mechanical properties of ores are carried out without considering peculiar properties of formation of geological, statistical conditions and patterns of distribution of properties. The knowledge about the distribution of the property of mineral deposits is highly important in solving geological and geometrical, mining and technological problems [3, 4]. The estimation of average values of structural and mechanical properties of real values of the main component content is often followed by systematic errors due to weak correlations of such interrelations.

The abovementioned aspects induce to substantiate new methods for assessing the distribution of structural and mechanical properties of mineral deposits, the use of which would allow taking into account diversity, interconnectivity and features of geological and statistical conditions of their distributions in solid. The developed method is based on calculation of prediction estimates of mean value and the mode, which allow providing the accuracy of the estimates with incomplete information, and when the type of the studied property distribution is unknown.

2. Estimating technique

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To study empirical distributions the set of structural properties have been used, including the power of ores and inter-mineral inclusions, bedding angles and fracturing rates: the set of physical and mechanical properties comprises density values, volume weight, angles of internal friction, porosity, the Poisson's ratio, static and dynamic modules of elasticity, compressive and tensile resistance, specific cohesion, deformation modulus, rock failure angles [5].

The estimation procedure of the mean value of structural and mechanical properties includes two methods, corresponding to two geological and static conditions of the exploration degree of deposit property:

a) cases, where the mode of the deposit property is known, and available information allows to determine it;

b) cases, where the mode of the property is unknown, as well as its distribution function is unknown.

The first method for estimation of the mean value of the property derives from the direct approach principle and it is based on the use of structural and regression equations. In this case the estimation of the mean value of the property is performed using the derived structural and regression equations presented in table 1.

The statistical analysis has been carried out with the major structural properties and physical and mechanical properties. Further, the following distribution parameters have been selected as initial basic parameters: the mean (X_{av}), the mode of (X_0) the property and of the property distribution characteristics: the mean square deviation (σ), the variation amplitudes (d), the degree of uniformity of the property distribution in the solid ore (H).

At the same time one or two-parameter equations are appropriate to use for prediction estimate when there are no other initial parameters:

$$X_{av} = A_1 \exp(X_0), \quad X_{av} = A_2 F(X_0, \sigma), \quad X_{av} = A_3 F(X_0, d), \quad X_{av} = A_4 F(X_0, H). \tag{1}$$

It is recommended to use three or four-parametric structural regression equations to estimate the average value of the property:

$$X_{av} = A_5 F(X_0, \sigma, d), \quad X_{av} = A_6 F(X_0, \sigma, H). \tag{2}$$

Structural and regression equations have inherent high values of the correlation ratio and the coefficient of determination (R = 0.94). It proves their suitability for estimation of the mean values of the property. The sequence of calculating the mean value of the property by this method is simple, but it is necessary to determine the type of distribution. The density function of the determined type of the property distribution can also be used for estimation of the mean value.

The stage of a direct approach, which does not require obligation of a preliminary determination of the type of the considered property distribution, has been set on the second method. This makes this estimation method highly important. The method is based on the use of derived structural and regression equations which are composed of parameters: amplitude, the mean square deviation and the uniformity coefficient of the property distribution. In this case, the type of the property distribution and its mode are omitted.

There are used one-parameter structural and regression equations for the prediction estimate of the mean value:

$$X_{av} = B_1 F(k_1, \sigma), \quad X_{av} = B_2 \cdot F(k_2, d). \tag{3}$$

It is recommended to use two or three-parameter equations for estimation of the mean value of the property:

$$X_{av} = C_1 F(\sigma, d), \quad X_{av} = C_2 F(\sigma, H), \quad X_{av} = C_3 F(d, H), \quad X_{av} = C_4 F(\sigma, d, H). \tag{4}$$

Exploration data can be used to determine values of the variation amplitude, standard deviation and indicators of uniformity property of the property distribution, when their values cannot be directly calculated. It is not always possible to reliably determine the type of the distribution function for each studied property due to insufficient information, and also because of the complexity of finding a

suitable distribution type. The developed rational estimation procedure of the property mode allows eliminating these deficiencies and it provides for the accuracy of determination of the property mean value.

Table 1. Structural relationships between the distribution parameters and the property distribution characteristics.

Structural and regression equations	Statistical parameters	
	Correlation coefficient	Number of observations
I. Single-parameter models		
$X_{av} = 0.86 + 1.15X_0$	0.73	104
$X_{av} = 2.69\sigma^{0.59}$	0.94	107
$X_{av} = 5.62 - 0.42H$	-0.21	107
$X_{av} = 0.63d^{0.75}$	0.82	105
$X_0 = 0.62d^{0.601}$	0.61	94
$X_0 = 13.8H^{-4}$	-0.12	113
$\sigma = 0.51d^{0.71}$	0.89	111
$\sigma = 0.30 + 0.2d$	0.94	113
$\sigma = 6.01H^{-0.47}$	-0.16	118
$d = 19.0H^{-0.47}$	-0.15	113
II. Two-parameter models		
$X_{av} = 0.13X_0 + 0.70\sigma + 0.09$	0.94	104
$X_{av} = 0.73X_0 - 0.14H - 0.16$	0.73	103
$X_{av} = 0.80\sigma - 0.35H - 0.45$	0.94	104
$X_{av} = 0.78d - 0.03H - 0.50$	0.82	104
$X_{av} = 0.94X_0 + 0.57d - 0.03$	0.87	104
$X_{av} = 0.93\sigma + 0.04d + 0.15$	0.94	104
$X_0 = 1.23\sigma + 0.10d + 1.11$	0.70	103
$X_0 = 1.23d - 0.03H - 0.81$	0.61	103
$X_0 = 0.72\sigma - 0.07H - 0.85$	0.70	103
$X_0 = 0.43X_{av} + 0.38\sigma + 0.16$	0.73	104
$X_0 = 2.44X_{av} + 0.81d + 1.57$	0.73	104
$X_0 = 0.73X_{av} - 0.06H - 1.06$	0.73	104
III. Three-parameter models		
$X_{av} = 0.12X_0 + 0.82\sigma + 0.03d - 0.54$	0.94	104
$X_{av} = 0.91\sigma + 0.55d - 0.08H + 0.46$	0.70	103
$X_0 = 0.81\sigma + 0.04d - 0.02H - 0.78$	0.74	103
IV. Four-parameter models		
$X_{av} = 0.15X_0 + 0.82\sigma - 0.04d - 0.07H + 0.21$	0.94	103
$X_0 = 0.92X_{av} + 0.05\sigma + 0.55d - 0.07H - 0.35$	0.74	104

The estimation procedure of the mode of a structural and mechanical property is based on deducting the structural and regression ratio between distribution parameters and property distribution characteristics. The mode as the most probable property value is the one of its important numerical characteristics. It is less affected by errors as well as the median. In comparison with the median and other static parameters, the mode is characterized by relatively high information content, a high degree

of influence on the level of the mean value and the efficiency of estimation, prediction and stabilization of the ore quality, when solving problems on estimation of the opening strength.
The prediction estimation of the mode of the property by applying the developed method is carried out with one or two-parameter structural and regression equations:

$$X_0 = B_{01} \cdot F(\varphi_1, \sigma), \quad X_0 = B_{02} \cdot F(\varphi_2, d), \quad X_0 = B_{03} \cdot F(\varphi_3, H). \tag{5}$$

To calculate the mode of the property two and three-parameter equations are used:

$$X_0 = C_{01} \cdot F(\sigma, d), \; X_0 = C_{02} \cdot F(d, H), \quad X_0 = C_{03} \cdot F(\sigma, H), \quad X_0 = C_{04} \cdot F(\sigma, d, H). \tag{6}$$

The analysis of the results of correlation analysis gave us:

- a close linear relationship in the dependence $X_{av} = F(X_0)$ and there is a less inversely proportional relationship in the dependences: $X_{av} = F(H)$, $X_0 = F(H)$, $\sigma = F(H)$;
- a significant nonlinear directly proportional relationship in the dependence: $X_0 = F(d)$;
- a close nonlinear directly proportional relationship in the dependences: $\sigma = F(d)$, $X_{av} = F(\sigma)$, $X_{av} = F(d)$;
- a close directly proportional relationship in the dependences: $X_{av} = F(\sigma, H)$, $X_{av} = F(X_0, \sigma)$, $X_{av} = F(X_0, d)$, $X_0 = F(X_{av}, \sigma)$, $X_0 = F(X_{av}, d)$, $X_{av} = F(X_0, d, \sigma)$, $X_{av} = F(X_0, \sigma, d, H)$;
- a significant directly proportional relationship in the dependences: $X_{av} = F(X_0, H)$, $X_{av} = F(d, H)$, $X_0 = F(X_{av}, H)$, $X_0 = F(X_{av}, \sigma, d, H)$, $X_0 = F(\sigma, d, H)$;
- an insignificant direct linear relationship in the dependences: $X_0 = F(\sigma, d)$, $X_0 = F(d, H)$, $X_0 = F(\sigma, H)$.

Based on the analysis of the results of the correlation analysis, it is found that the strength of a relationship between the mode and property distribution characteristics is slightly less (R = 0.67-0.82) whereas the degree of dependence between the mean value of the property and its distribution characteristics is high (R=0.90-0.94). The presence of a significant relationship between the distribution parameters and property distribution characteristics refers to the genesis of statistical structures and the geometry of deposit property distributions. The results of a comparative evaluation of the empirical distributions of structural and physical-mechanical properties characteristics according to the proposed estimation procedure has allowed to conclude the following:

- the distributions of values of ore and rock volume weights are best described by the normal distribution and the Weibull distribution. They are characterized by symmetrical curves and small values of asymmetry and kurtosis;
- the distributions of values of the density of ores and rocks are described by the lognormal distribution and the Weibull distribution; They have forms of curves that are close to symmetric, but related to the right symmetric distribution;
- the distributions of values of the angle of internal friction and the specific cohesion of rocks are described by the normal distribution and the Weibull distribution;
- the distributions of the values of porosity, modulus of deformation, static elasticity modulus of rocks, resistivity and fracture, the Poisson's ratio are described by the Weibull distribution. They have slightly right-handed forms of curves, for which the asymmetry values are above zero;
- the distributions of the values of compressive and tensile resistance are described by the exponential distribution and the Weibull distribution. They are characterized by moderately right-symmetric radial curves and significant values of asymmetry and kurtosis;
- the distributions of structural properties are characterized by symmetrical curves. The distributions of physical and mechanical properties are mostly mixed: symmetric, right-symmetric radial curves.

The dependences for the mean value and the mode of the property are carried out in the form of multifactorial equations. The results of the correlation-regression analysis of the relationship between the distribution parameters and property distribution characteristics are presented in table 2.

Table 2. The relationships between the distribution parameters and property distribution characteristics.

#	Types of dependence	Correlation coefficient	Number of observations	Equations of the relationship	
				Nonlinear	Linear
	I. Dependences between the mean value and other characteristics				
1	$X_{av} = F(X_0)$	0.73	104	$X_{av} = 1.44\exp(0.93X_0)$	$X_{av} = 0.86 + 1.15X_0$
2	$X_{av} = F(\sigma)$	0.94	107	$X_{av} = 2.69\exp(0.59\sigma)$	$X_{av} = 0.50 + 1.310\sigma$
3	$X_{av} = F(d)$	0.80	107	$X_{av} = 0.6\exp(0.75d)$	$X_{av} = 0.62 + 0.28d$
	II. Dependences between the mode value and other characteristics				
1	$X_0 = F(\sigma)$	0.70	103	$X_0 = 1.482\exp(0.638\sigma)$	$X_0 = 0.77 + 0.63\sigma$
2	$X_0 = F(d)$	0.61	115	$X_0 = 0.622\exp(0.61d)$	$X_0 = 0.69 + 0.151d$
3	$X_0 = F(H)$	-0.12	113	$X_0 = 13.H^{-1.01}$	$X_0 = 4.94 - 0.37H$
	III. Dependences between property distribution characteristics				
1	$\sigma = F(d)$	0.89	108	$\sigma = 0.51\exp(0.71d)$	$\sigma = 0.30 + 0.21d$
2	$\sigma = F(H)$	-0.16	118	$\sigma = 6.01H^{-0.52}$	$\sigma = 4.22 - 0.301H$
3	$d = F(H)$	-0.50	103	$d = 19.95H^{-0.47}$	$\sigma = 15.17 - 1.04H$

3. Conclusions

The method for estimation of the mean value and the mode of the property becomes important with increasing the depth growth of mining operations and the complexity degree of excavation sites, the growth of number of cases, when geological information volume representing the level of values of structural and physical-mechanical properties is insufficient. The reliability of estimates is achieved through the involvement of different characteristics of the studied property. The efficiency of the procedure is associated with possibility to determine the mean value and the mode regardless of its distribution function and when the volume of information is insufficient. The developed procedure can be used in making short- and long-term plans, technical and economic and process design solutions, in optimizing ore excavation conditions and mining operations, in substantiating the density of an exploration grid. Factual data from geological and surveying materials from Don, South Kempirsai chromite and Krasnooktyabrskiy bauxite mines have been used as experimental data.

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