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STOCHASTIC APPROACH TO ROOM-AND-PILLAR FAILURE IN OIL SHALE MINING

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Abstract. The stability of the mined areas in an oil shale deposit may decrease in the course of time. As a result, large areas may collapse after underground mines are abandoned. The traditional approach to calculating the stability of underground rooms is to use average parameters and to ignore the variability of rock properties. In addition, the formal method of calculating the bearing capacity of pillars takes into consideration short-term safety and overlooks the weakening of the water saturated rock. This paper describes the results of stochastic modelling of the long-term decrease in the bearing capacity of the pillars, including the case of drowned mines. Continuous pillar weakening and the increase in the probability of room collapse are considered.

Key words: room-and-pillar mining, collapse, bearing capacity, moisture, stochastic approximation method.

1. INTRODUCTION

Room-and-pillar mining, a partial mineral extraction method, protects against roof caving during mining, whereas the surface of the ground moves approximately in the range of twenty millimetres. In Estonia, over a period of forty years, an area of 92 km^2 has been subjected to room-and-pillar mining [1]. Pillar failures (Fig. 1), room collapses, and surface subsiding of 1.5–2 m have been estimated approximately on 2% of the area. Surface subsiding is causing problems for agriculture and forestry (Fig. 2). As a result of air shocks from collapses, underground constructions have been destroyed and miners injured.

In connection with closing the mines and abolishing the responsibilities by the enterprises, the question about stabilizing the areas subjected to the partial extraction mining system arises. It should be noted here that closed mines are drowned, which affects the bearing capacity of the pillars. Collapses in water-filled mines and the resulting water shocks are dangerous. However, probability of their occurrence has not been determined [2].

Fig. 1. Failed pillar in a collapsed room of the Ahtme mine in April 1965.

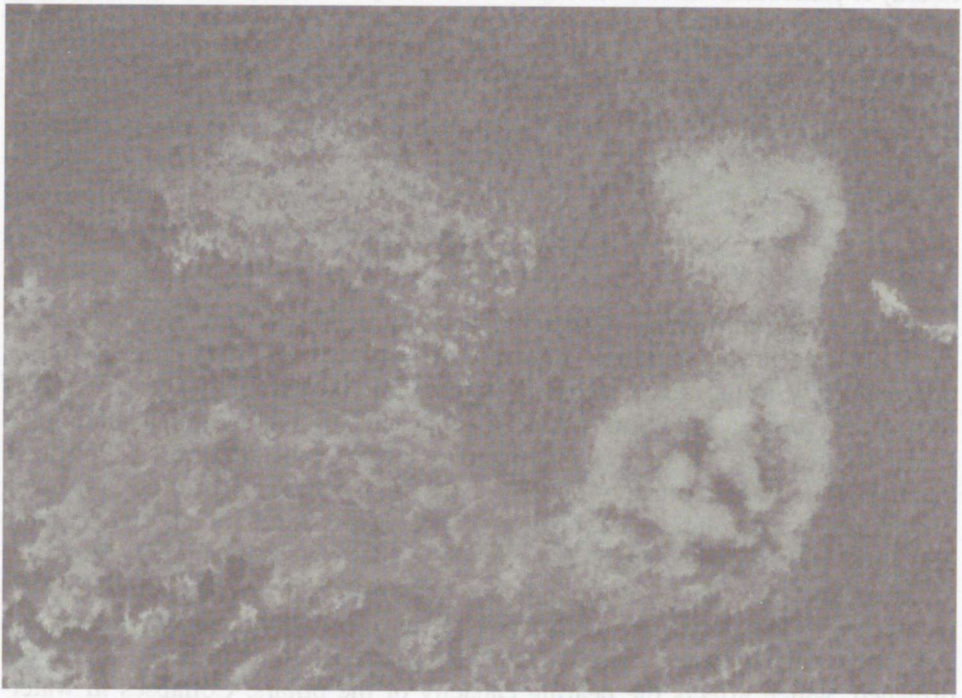

Fig. 2. Deformed land cover over collapsed rooms.

The majority of room collapses have been recorded during or immediately after stoping. The collapses in the mined-out areas are typically not recorded or occasionally not even noticed. Thus, an opinion has emerged that further collapses of rooms are unlikely to occur and that the mined areas will remain unaltered.

2. BASIC CONCEPTS

To calculate the bearing capacity of the pillars, a formula developed at the Institute of Mining Surveying (IMS), St. Petersburg [3], is being used:

$$k = \alpha + \beta(1/(1+t))^m , \tag{1}$$

where k is the rate of current rock strength, t is time, and α, β, and m are empirical coefficients. Equation (1) was derived on the basis of observations in oil shale mines. Average value of the coefficient α, which shows the rate of the stabilized strength, is 0.44. Coefficients β and m determine the decrease in the rock strength: $\beta = 1 - \alpha = 0.56$ and $m = 0.6$ (if time t is measured in months). According to [3], the precision of Eq. (1) could reach $\pm 30\%$ for single measurements and $\pm 12\%$ on average. Our estimation of the standard deviation is 0.0908, based on the method described below. Equation (1) describes a hyperbolic dependence according to which the value of k decreases from 1 (basic strength at $t = 0$) to 0.44 (stabilized strength at $t = \infty$).

3. UNCERTAINTY

The basic concept of the IMS method is that the strength of the rock pillar is characterized by two factors: basic and stabilized strength. Basic strength characterizes rocks by fast loading, e.g., by pressure testing. Under constant pressure, the current strength of the rock decreases and after some time it equals the stabilized strength. This perception of rock behaviour complies with the concept of creep. Such phenomena as rock weathering, technological deviations and deviations in rock strength are regarded as anomalies. Increased moisture content of the oil shale has been reported as a reason of at least one collapse [4]. To eliminate the effect of anomalous factors, the method based on the theory developed by the IMS uses the safety factor, the value of which is from 1.1 to 1.4.

Observation data, which served as a basis for Eq. (1), were taken from a graph in [5] and are shown in Table 1.

To check the reliability of the empirical coefficients proposed by IMS, we shall use the data given in Table 1. Equation (1) can be linearized as follows:

$$\ln(k - \alpha) = \ln \beta + m \ln(1/(1+t)) . \tag{2}$$

Table 1. Observation data according to graph in [5]; t – time in months

No.	t	k	No.	t	k	No.	t	k
1	0.4	0.810	18	4.8	0.670	35	12.0	0.450
2	0.6	0.780	19	5.8	0.640	36	13.0	0.530
3	0.7	0.930	20	6.0	0.670	37	13.0	0.495
4	0.7	0.770	21	6.0	0.440	38	13.2	0.600
5	0.8	0.990	22	6.0	0.420	39	15.0	0.560
6	0.8	0.780	23	6.0	0.675	40	15.7	0.500
7	1.4	0.815	24	6.0	0.490	41	16.5	0.550
8	1.8	0.660	25	6.5	0.610	42	17.0	0.640
9	2.0	0.670	26	6.9	0.440	43	18.0	0.510
10	2.0	0.970	27	7.4	0.490	44	18.5	0.560
11	2.4	0.720	28	7.9	0.680	45	33.0	0.460
12	2.8	0.610	29	8.2	0.500	46	37.5	0.450
13	3.3	0.630	30	8.3	0.620	47	38.0	0.480
14	3.7	0.600	31	8.6	0.470	48	46.0	0.570
15	4.0	0.520	32	8.7	0.630	49	55.0	0.610
16	4.0	0.540	33	8.8	0.570	50	58.0	0.630
17	4.1	0.740	34	11.8	0.510	51	58.6	0.530
						52	59.0	0.460

Using notations

$$Y = \ln(k-\alpha),\ \ A = \ln\beta,\ \ X = \ln(1/(1+t)), \tag{3}$$

we obtain a linear equation

$$Y = A + mX. \tag{4}$$

This equation can be processed by the regression method. However, if $k \le 0.44$, the logarithm in (3) is not a real number and transformation of the equation fails. Thus, parameters α and β may be given new values: $\alpha = 0.418$, which is smaller than the smallest observed value of k; accordingly, $\beta = 1 - 0.418 = 0.582$. Since one of the outputs of the regression method is parameter A with $\beta = \exp A$, it is clear that the regression analysis of the data does not support the relation $\beta = 1-\alpha$. In any case, $\alpha + \beta < 1$. It implies that by pillar formation, rock strength does not correspond to its basic strength any more. In other words, Eq. (1) which describes the rock weakening from its basic strength 1 to the final level α, may not be valid. In terms of mining engineering the explanation is simple – under rock pressure, rock weakening starts before pillar formation and rock is characterized by its current strength rather than by its basic strength.

On these grounds, we made the regression analysis of the data with α varying from 0 to 0.418, neglecting the condition $\alpha + \beta = 1$. The best correlation (range 0.64) was obtained with $\alpha = 0$, $\alpha + \beta = 0.79$, and $m = 0.133$, with the standard deviation of 0.0969. The following two preliminary conclusions may be drawn:

1) at the moment of pillar formation, rock strength has already decreased;
2) the final rock strength of the pillar may be very small.

4. DEDUCTION OF A NEW RELATION

The results of our preliminary analysis allow us to use a decreasing function for describing the factor of strength, the argument of which incorporates the time during which the strength of the rock, forming a pillar, is reduced before pillar formation. We denote this by z. Exponential and power functions, which can be combined, are simpler for describing the decreasing values. However, it should be noted that these functions are easy to be linearized by finding the logarithms of k and t, whereas the resulting distorted source data make the results of the regression analysis unreliable. Therefore the estimated standard deviation (0.0969) of the result obtained by the regression analysis of Eq. (4) is relatively high.

Next, we shall use the simplest stochastic approximation method. In this method, the parameters α, β, and m are given random values and the calculated values of k are compared with the observed data using root-mean-square (rms) estimation. Calculations are repeated until the minimum of the rms estimation and of the standard deviation are achieved.

To find the best relation satisfying the source data, four formulas (models) were analysed. The first one was Eq. (1), others were:

the transformed IMS formula with the time factor

$$k = \alpha + (1-\alpha)(1/(1+(t+z)))^m, \tag{5}$$

the exponential model

$$k = \alpha + (1-\alpha)\exp(-\delta(t+z)), \tag{6}$$

and the improved exponential (the Rosin–Rammler or Weibull) model

$$k = \alpha + (1-\alpha)\exp(-\delta(t+z))^m. \tag{7}$$

In all the models, z is the time (in months) during which rock weakening takes place before pillar formation, and in exponential models δ is the coefficient which characterizes the intensity of rock weakening. Table 2 shows the parameters of all the models. Graphs are shown in Figs. 3 and 4.

Analysis of the models enables us to draw the following conclusions:

1) the current strength of the rock has decreased for the moment of pillar formation,

2) the value of the rock's final strength is close to zero,

3) exponential models describe rock weakening better than the power function,

4) divergence between the measured and the calculated weakening intensity is relatively independent of the model type.

Table 2. Parameters of the models

Formula	α	z	δ	m	k $(t = 0)$	Standard deviation
(1)	0.440	0	–	0.60	1	0.0908
(5)	0.415	0.067	–	0.58	0.98	0.0902
(6)	0.544	0.160	0.39	–	0.97	0.0857
(7)	0.544	0.391	1.04	0.39	0.93	0.0849

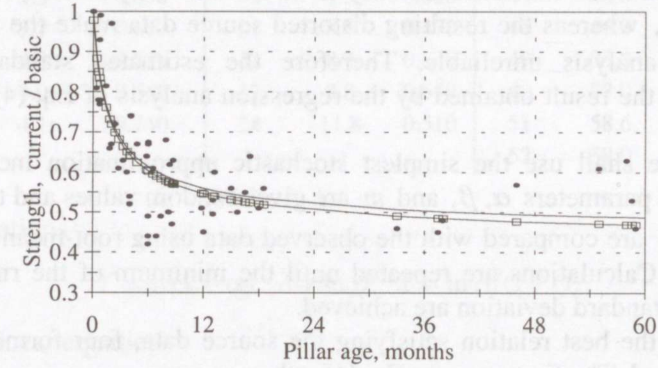

Fig. 3. Rock weakening during pillar formation; power-type models: ● observation data, — IMS original model, □ IMS model with the time factor.

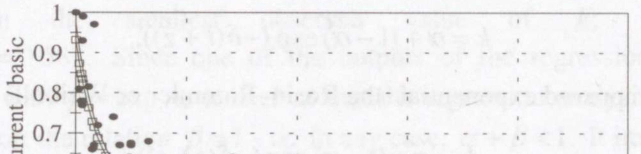

Fig. 4. Rock weakening during pillar formation; exponential-type models: ● observation data, — exponential model, □ Rosin–Rammler model.

5. EVALUATION OF THE PROBABILITY OF ROOM COLLAPSE

To create a basis for evaluating pillar failure, we analysed the models and their divergence characteristics. The ultimate bearing capacity of the pillars was based on their type and dimensions (stope pillar, protective pillar, or barrier pillar) and on the current strength of the rock. The stability of stope pillars was determined at least for two years, but for protective and barrier pillars, for an indefinite time. Accordingly, current strength after two years or stabilized strength was used and in the calculations the safety factor was from 1.1 to 1.4. In practice, safety is not steady. It can change because of geological situation, violations of technology, and collapses in the stoped out area. Based on the standard deviations mentioned above and assuming a normal distribution of the deviations, Table 3 shows the probability of pillar failure and room collapse during twenty years after stoping. The results exclude the pillar weakening influenced by water. The calculation results are demonstrated in Fig. 5.

Table 3. Probability of room collapse during twenty years after stoping, %

Safety factor	IMS original formula	IMS formula with the time factor	Exponential model	Rosin–Rammler model
1.1	32.2	32.9	28.2	28.0
1.2	19.9	20.8	14.5	14.3
1.3	12.1	13.0	7.2	7.0
1.4	7.3	8.2	3.5	3.4

Table 3 shows that the improved model has not removed the ambiguity involved in the evaluation of the probability of room collapse. We conclude tentatively that the probability of collapse depends on the safety factor of the bearing capacity of the pillar.

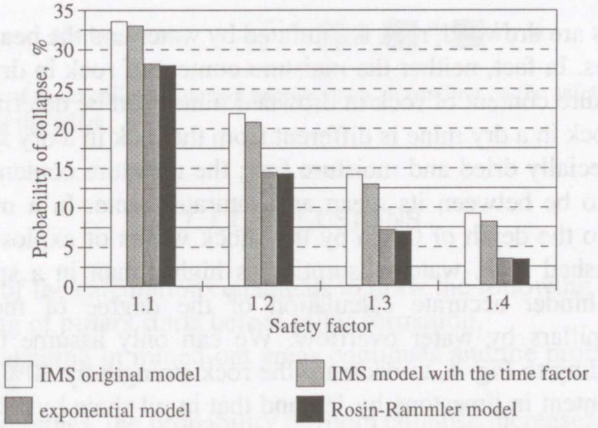

Fig. 5. Probability of room collapses during twenty years, depending on the safety factor of pillar stability and on the calculation model.

6. EFFECT OF MOISTURE ON COLLAPSE FORMATION

Rock strength depends on the moisture content. Under water-saturated conditions, the strength of most of the sedimentary rock is lower than in dry conditions. In particular, this applies to claystone. The difference between the strength of water-saturated and dry specimens is twofold, whereas that of some East-Donbass claystone is even higher, from 1.6 to 8.3 [4]. Likewise, oil shale bed rocks have different moisture content: water-saturated oil shale specimens are from 1.4 to 1.7 times, marl and clayey limestone for 1.4 times, and dolomith and loamy limestone from 1.1 to 1.25 times weaker than dry specimens [5]. IMS results [4] concerning the dependence of oil shale bed rock strength on the moisture content are shown in Fig. 6.

Table 4 characterizes the tests on which the empirical relations between the moisture content and strength of the rock were based [4,6]. Reduction in the relative rock strength, calculated using these relations with an increase in the moisture content, is shown in Fig. 6.

Table 4. Rock properties shown in Fig. 6

Rock properties	Oil shale bed [4]		Coal seam and floor [6]		
	Limestone	Oil shale	Claystone	Siltstone	Weak floor strata
Specific weight, kN/m^3	24.8–24.9	12.6–13.5			
Effective porosity*, %	6.52–8.24	14.31–16.86			
Water receptivity**, %	2.62–3.33	10.01–11.49			
Density***, Mg/m^3			2.62/0.15	2.54/0.14	2.54/0.16
Moisture content***, %			6.45/2.87	4.46/3.00	5.27/2.90

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* water-admissible pore content by volume,

** highest moisture content achieved in laboratory conditions by mass,

*** arithmetic mean/standard deviation.

When mines are drowned, rock is saturated by water and the bearing capacity of pillars decreases. In fact, neither the moisture content of rock in dry mines nor the degree of moisture content of rock in drowned mines can be determined precisely. Furthermore, rock in a dry mine is different from the rock in a dry specimen. A dry specimen is specially dried and moisture free; the moisture content of a dry mine rock is likely to be between its mean and saturated state. In a mine, pillars are influenced up to the depth of 0.5 m by the shock waves of explosion, and within the area of crushed rock, water absorption is higher than in a specimen. These circumstances hinder accurate calculation of the degree of moisturizing and weakening of pillars by water overflow. We can only assume the results. For instance, according to Fig. 6, to decrease the rock strength by 10%, an increase of the moisture content in limestone by 1% and that in oil shale by 4% are sufficient. Let us assume that such increase in moisture content is realistic and discuss how the probability of failure increases when pillar strength decreases by 10%. Our calculation results are shown in Fig. 7.

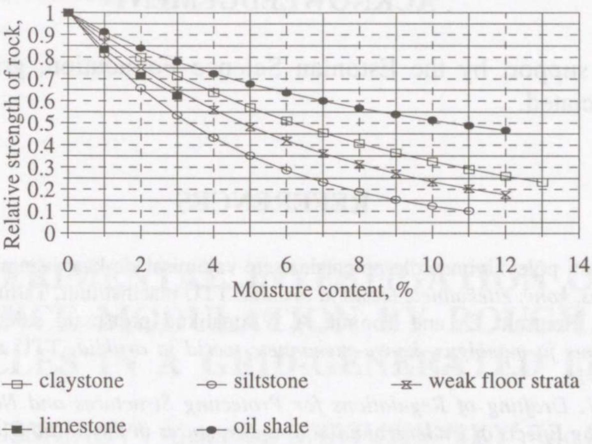

Fig. 6. Dependence of the strength of sedimentary rock on the moisture content; the data for claystone, siltstone, and weak strata of coal seam is taken from [6], for limestone and oil shale from [4].

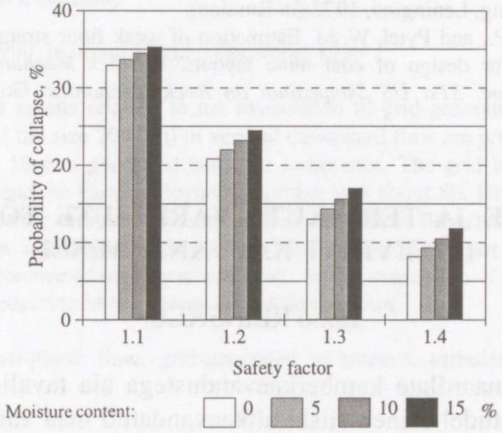

Fig. 7. Probability of room collapses during twenty years, depending on the safety factor and on the moisture content of the pillar.

7. CONCLUSIONS

The results of the calculations enable us to draw the following conclusions:

1) weakening of pillars starts before pillar formation,

2) pillar weakening in mined-out areas continues and the probability of room collapse remains,

3) in flooded mines, the probability of room collapse increases.

These conclusions urge us to handle the post-technological processes, caused by pillar and room collapse in abandoned mines, with great care.

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KAMBRITE JA TERVIKUTE VARINGUTE TÕENÄOSUS PÕLEVKIVI KAEVANDAMISEL

Enno REINSALU

Eesti põlevkivimaardlate kamberkaevandustega ala tavaliselt märgatavalt ei vaju. Üksikutel juhtudel esineb siiski altkaevandatud maa varinguid. Seni ei ole teada, kas varingud on tingitud tehnoloogilistest või geoloogilistest hälvetest. Artiklis on püütud hinnata varingute teket kirjanduses avaldatud andmete tõenäosusliku interpreteerimise teel. On käsitletud nelja tervikute kandevõime vähenemist kirjeldavat mudelit nii kivimi õhkkuiva kui ka veega küllastunud oleku puhul. On püstitatud hüpotees, et tervikute kandevõime väheneb intensiivsemalt kaevanduste veega täitumisel.