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SAFETY FACTOR OF PILLARS

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This paper deals with the formula for changes in oil shale bed rock durability in Estonian deposit, and discusses possible deviations of rock durability and their probability. It also establishes the dependence of pillars on durability deviation scale, offers their theoretical age and actual safety factor.

Rooms and intervening pillars are constructive elements of the room-and-pillar mining systems. Many technical and economic parameters of production, including loss of oil shale reserves, depend on a correct choice of the sizes for these elements.

Rock strength data are of a determinant importance for the choice of the sizes of constructive elements used in room-and-pillar mining. Without taking into account the rheologic properties of rock, in particular the character of the change in their long-term durability, the calculation of the sizes of rooms and pillars for a certain term is impossible.

The character of changes in durability of oil shale bed and roof limestone strata is described with sufficient accuracy by the following empirical formula of VNIMI:

$$k_t = \alpha + \beta\left(\frac{1}{1+t}\right)^m \tag{1}$$

where k_t - factor of the change in durability of rocks in time, equal to the relation of current durability R_t to the start durability R_0;

α, β, m - empirical factors, reflecting properties of rocks ($\alpha =$ $= 0.44$; $\beta = 0.56$; $m = 0.6$);

t - service life of pillars or rooms (months).

When the service life of pillars t approaches infinity ($t \to \infty$), the limit value of factor k_t equals 0.44.

Proceeding from the Formula (1), the durability of Ordovician rocks in conditions of the Baltic Oil Shale Basin can be established by using the expression

$$R_t = k_t R_0 \qquad (2)$$

The average values of start durability and the limit of long-term durability of oil shale layer in Estonian deposit should be accepted as following:

$$R_0 = 16 \text{ MPa}; \ R_\infty = 7.0 \text{ MPa}.$$

It is necessary to consider that dispersions of R_t values may be as follows: average ±12 %, maximum ±30 %. The probability that R_t values deviate on the average 12 %, makes 0.16, and the corresponding number for maximum dispersion 30 % is equal to 0.01.

The calculation of pillars for more than 5 years should be carried out aimed at long-time durability, i.e. one has to accept that $R_t = R_\infty$.

The calculation of pillars, considering the need of permanent use during 2 years (the time necessary for the winning of all rooms in the block), is accomplished according to the Formulae (1) and (2), where the value of current durability R_t = 8.3 MPa.

The dependence of durability of rocks on time and on dispersion of durability from average values is shown in Fig. 1.

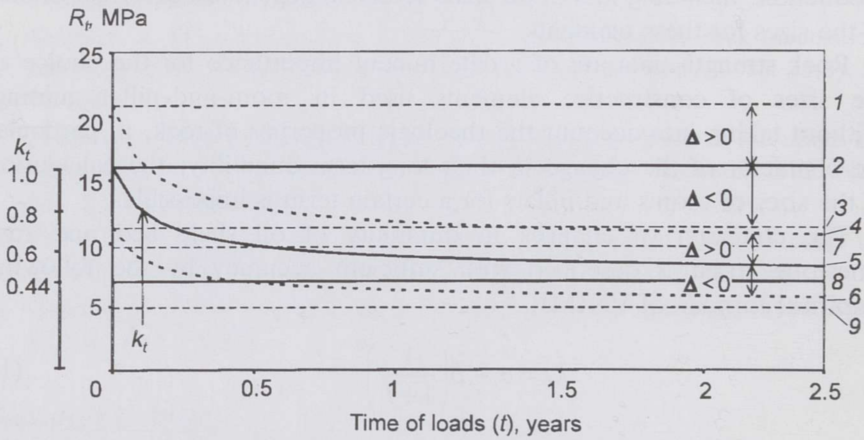

Fig. 1. Dependence of durability of rocks on time:
1 - $R_{0\max} = R_0(1 + \Delta)$; *2* - R_0 = 16 MPa; *3* - $R_{0\min} = R_0(1 + \Delta)$; *4* - $R_{t\max} = k_t R_{0\max}$; *5* - $R_t = k_t R_0$; *6* - $R_{t\min} = k_t R_{0\min}$; *7* - $R_{\infty\max} = R_\infty(1 + \Delta)$; *8* - R_∞ = 7 MPa; *9* - $R_{\infty\min} = R_\infty(1 - \Delta)$; at $\Delta = 0.3$ $R_{\infty\max}$ = 9.1 MPa, at $\Delta = -0.3$ $R_{\infty\min}$ = 4.9 MPa;

$$k_t = 0.44 + 0.56111\left(\frac{1}{1+t}\right)^{0.6}$$

In order to define the sizes of pillars for any purpose, it is necessary to proceed from the following equation:

$$nP_f = P_b \tag{3}$$

where n - reserve (or factor of a stock) of strength of pillars;

P_f - actual load on pillars;

P_b - bearing ability of pillars.

If a downfall of main roof does not occur, then P_f remains constant.

P_b can be characterized as follows:

$$P_b = k_f R_t S \tag{4}$$

where k_f - factor of the pillar form;

S - cross-sectional area of a pillar.

Hence, in a current moment of time t it is possible to determine the safety factor of pillars n_t using the formula

$$n_t = \frac{P_b}{P_f} = \frac{k_f R_t S}{P_f} \tag{5}$$

If $t = t_a$, where t_a is the assumed or given service life of pillars, and $R_t = R_a$, where R_a is the start durability of rocks (in the moment of time at which they are designed) then the relationship between the given factor of safety n and other parameters of pillars remains similar to (5):

$$n = \frac{k_k R_a S}{P_f} \tag{6}$$

$$\frac{n_t}{n} = \frac{R_t}{R_a}; \quad n = \frac{R_t}{R_a} n \tag{7}$$

where n_t - the actual safety factor of pillars in a current moment of time t.

In the cases when the durability of rocks (R_0 and R_t) remains below the average values, i.e. < 0 (Fig. 1), it becomes necessary to set factor of a stock in accounts $n > 1$. Since it is not known when, where and how much R_0 and R_t differ from their average values, one can presume that at an identical age of pillars t_p the values of R_a have everywhere identical average values at which pillars pay off. The probable dispersions of R_0 and R_a from average values Δ are compensated by factor of a stock n, which values are chosen depending on the gravity of surface objects. For the second class objects n = 1.3-1.4, for the third class objects n = 1.2-1.3 (in near-carst areas n = 1.3). Values of R_t also remain within the limit of $R_t \pm \Delta$, and hence

$$n_t = \frac{R_t + \Delta}{R_a} n \tag{8}$$

At the initial moment of time (at $t = 0$) without rock creep $R_t = R_0$. The values of R_a depend on the service life for which pillars were designed. If they are designed for an indefinitely long term, then at $t \to \infty$ also $R_a \to \infty$. According to the Eqs. (1) and (2), it becomes possible to make the following conclusion:

If $k_t \leq 0.44$ or $k_t = 1$, creep of rocks does not occur.

This phenomenon occurs only in such a case if load on pillars is less, or the actual safety factor of pillars exceeds a certain limit that is necessary for the beginning of creep. In the first case

$$\frac{1}{k_t} \geq 2.3 \text{ or } \frac{R_0}{R_t} \geq 2.3 \text{ (here } R_t = R_\infty \text{)}$$

The last equation represents the safety factor of rocks at the initial moment of time if pillars are designed for $t = \infty$ (at $t = 0$ and $n = 1$). In other words: if $n_t \geq 2.3$, creep of rocks does not occur.

Hence follows that even if

$$\frac{R_a + \Delta}{R_a} < 2.3, \text{ but } \frac{R_a + \Delta}{R_a} n \geq 2.3$$

creep of rocks does not occur. In such a case $R_t = R_0$. In the second case ($k_t = 1$) also $R_t = R_0$.

Expressing the probable dispersions of rock durability Δ in shares R_t, Formula (8) will take the following form:

$$n_1 = \frac{k_1 R_0 (1 + \Delta)}{R_0} n \qquad (9)$$

Below some cases of n_t dependence will be explored:

(1) For intervening pillars (IVP) designed for unlimited supporting of the main roof ($t = \infty$)

(2) For IVP designed for the term of winning the block (for 2 years)

(3) For barrier pillars designed for unlimited supporting of the main roof and located around a protected zone within intervening pillars, also designed for ($t = \infty$)

(1) If IVP are designed on $t = \infty$, then $R_a = R_\infty$, and $\frac{R_0}{R_\infty} \approx 2.3$

At the initial moment of time ($t = 0$), $k_t = 1$, hence: until $(1 + \Delta)n \geq$ ≥ 1, creep of rocks does not occur.

If the given factor of stock $n = 1.3$, it is valid at values $\Delta \geq -0.23$. At $n = 1.3$ and $\Delta < -0.23$, creep of rocks begins. It lasts as long as $n_t \geq 1$. Assuming that the pillars will collapse at $n_t = 0.999$ with $\Delta = -0.24$, the creep will take place in approximately 600 years.

In order to determine the collapse time of pillars t from Formula (9), we should set the value of k_t at $n_t = 0.999$:

$$k_1 = \frac{n_1 R_\infty}{R_0(1+\Delta)n} = \frac{0.999 \times 7}{16(1-0.24)1.3} = 0.44237$$

For such a value of k_t the corresponding age of pillars equals ≈600 years. If the divergence of strength of rocks from average values reaches 30 % ($\Delta = -0.3$), then at $n_t = 0.999$, $k_t = 0.4803$. In such a case the collapse of pillars will take place in approximately 6.5 years (Fig. 2). The probability of such values remains negligible and the collapse may occur only occasionally.

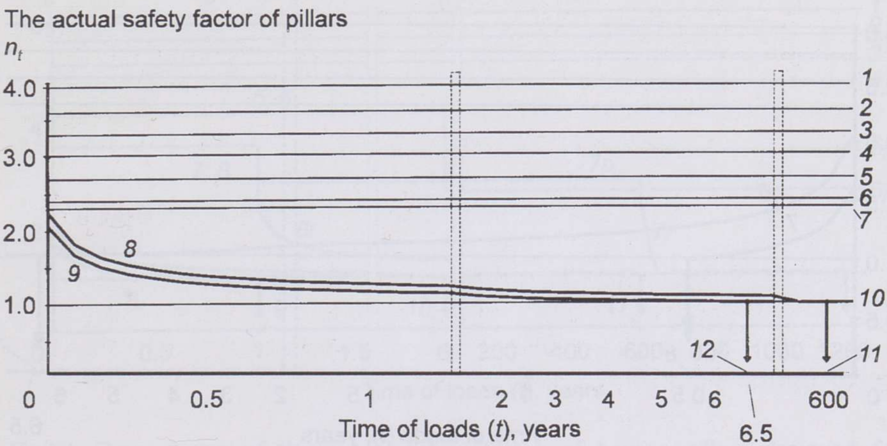

Fig. 2. Dependence of the actual safety factor for IVP designed for unlimited supporting of the main roof on time (at the given value of safety factor $n_t = 1.3$):
1-7 - in the absence of rock creep, i. e. at $(1 + \Delta)n \geq 1$: *1* - at $\Delta = 0.3$; *2* - at $\Delta = 0.2$; *3* - at $\Delta = 0.1$; *4* - at $\Delta = 0$; *5* - at $\Delta = -0.1$; *6* - at $\Delta = -0.2$; *7* - at $\Delta = -0.23$;
8 and *9* - in the presence of rock creeps, i. e. at $(1 + \Delta)n < 1$: *8* - at $\Delta = -0.24$, *9* - at $\Delta = -0.3$;
10 – the actual safety factor $n_t = 1$; *11* and *12* – the moment of loss of supporting ability of pillars (*11* - at $\Delta = -0.24$, *12* - at $\Delta = 0.3$); Δ - dispersion of durability of rocks from average values (in shares of durability of rocks)

(2) If IVP are designed for 2 years, $R_a = 8.339$.
At the initial moment of time (at $\bar{t} = 0$) and at a presumed value of $n = 1.2$, $k_t = 1$ and $n_t > 2.3$. Hence, while the values Δ and n remain as follows: $\Delta \geq 0$ and $n \geq 2.3$, creep of rocks does not occur and MVP will stand for an indefinitely long time. Creep of rocks will begin at $n \approx 1.2$ and $\Delta < 0$.

If $\Delta = -0.1$, collapse of pillars will take place in approximately 78 months (6.5 years), if $\Delta = -0.3$, collapse of pillars will take place in approximately 6 months (0.5 years) (Fig. 3).

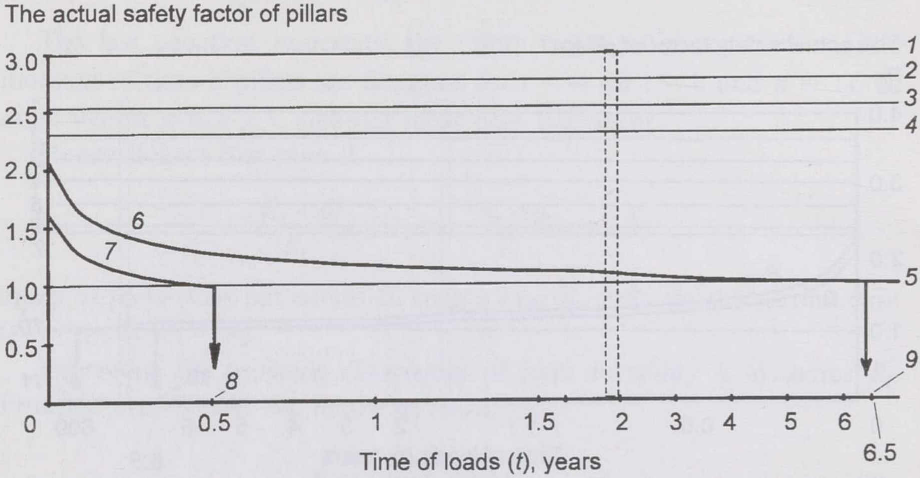

Fig. 3. Dependence of the actual safety factor for VP designed for 2 years on time (at the given value of safety factor $n = 1.2$).
1-4 - in the absence of rock creep, i. e. at $n_t \geq 2.3$: *1* - at $\Delta = 0.3$; *2* - at $\Delta = 0.2$; *3* - at $\Delta = 0.1$; *4* - at $\Delta = 0$;
5 - the actual safety factor $n_t = 1$;
6 and *7* - in the presence of rock creeps, i. e. at $n_t < 2.3$ (*6* - at $\Delta = -0.1$, *7* - at $\Delta = -0.3$);
8 and *9* - the moment of loss of supporting ability of pillars (*8* - at $\Delta = -0.3$, *9* - at $\Delta = -0.1$)

(3) Until the collapse of IVP outside of a protected zone has not yet occurred, the load on barrier pillars will remain about 1.6 times less than the limit for which they were designed. Hence, the actual factor of stock should exceed 1.6 times the value which is necessary for external line of barrier pillars directly after the collapse of IVP outside of a protected zone, i.e.

$$n_t = 1.6\frac{k_t R_0 (1+\Delta)n}{R_\infty} \quad (10)$$

If this occurs, then barrier pillars will hold the load for which they were designed. Together with the fall of main roof outside of defensible zone a quick reduction of actual safety factor n_t of barrier pillars will occur (Fig. 4). If afterwards $n_t \geq 2.3$, creep of rocks will not occur and pillars remain "eternal" (for example, at $n = 1.3$ and $\Delta > -0.23$; in Fig. 4 a case where $\Delta = -0.1$ is shown).

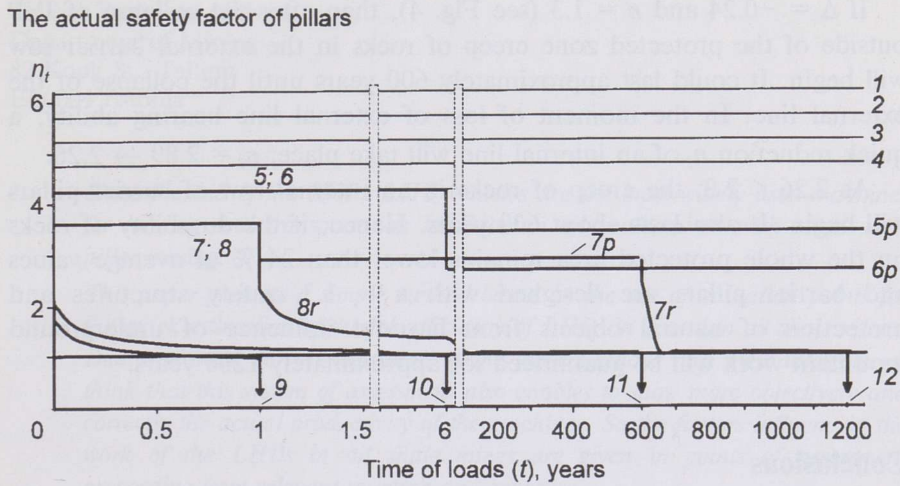

Fig. 4. Dependence of the actual safety factor of barrier pillars designed for unlimited supporting of the main roof on time (at the given value of safety factor $n = 1.3$).

1-8 - in the absence of rock creep, i. e. at $n_t \geq 2.3$: *1* - at $\Delta = 0.3$; *2* - at $\Delta = 0.2$; *3* - at $\Delta = 0.1$; *4* - at $\Delta = 0$; *5* and *6* - at $\Delta = -0.1$; *7* and *8* - at $\Delta = -0.24$ (up to the collapse of IVP located outside of protected zones);

5p-7p: *5p* and *6p* - at $\Delta = -0.1$; *7p* - at $\Delta = -0.24$ (after the collapse of IVP located outside of the protected area); *5p* and *7p* - for internal and *6p* - for external lines;

7r and *8r* - in the presence of rock creep, i. e. at $n_t < 2.3$, (*7r* - for internal and *8r* - for external lines, at $\Delta = -0.24$);

9 and *10* - the moment of collapse of IVP located outside of the protected area (*9* - at $\Delta = -0.24$, *10* - at $\Delta = -0.1$);

11 and *12* - the moment of collapse of barrier pillars at $\Delta = -0.24$ (*11* - for external and *12* - for internal lines)

After the collapse of pillars outside of the protected zone, the actual safety factor of barrier pillars can be calculated as following:

For an external line

$$n_t = \frac{k_t R_0 (1+\Delta) n}{R_\infty} \tag{11}$$

For an internal line

$$n_t = 1.28 \frac{k_t R_0 (1+\Delta) n}{R_\infty} \tag{12}$$

Due to an additional load that is caused by broken rocks in the blocks of main roof, the load of an internal line of barrier pillars will increase about 20 % accompanied by an equal decrease of n_t.

If $\Delta = -0.24$ and $n = 1.3$ (see Fig. 4), then after the collapse of IVP outside of the protected zone creep of rocks in the external barrier row will begin. It could last approximately 600 years until the collapse of the external line. In the moment of loss of external line bearing ability, a quick reduction n_t of an internal line will take place: $n_t = 2.89 \rightarrow 2.26$.

As $2.26 < 2.3$, the creep of rocks in an internal row of barrier pillars will begin. It also lasts about 600 years. Hence, if the durability of rocks on the whole protected area remains lower than 24 % of average values and barrier pillars are designed with $n = 1.3$, safety structures and protection of natural objects from harmful influence of underground mountain work will be guaranteed for approximately 1200 years.

Conclusions

1. There should be no creep by pillars intended to hold on beyond all bounds of time. As soon as creep will begin, pillars cease to be "eternal".
2. If creep of rocks occurs (at $n_t < 2.3$), the values of R_t will approach the value of R_a. At $\Delta = 0$, the actual factor of stock becomes equal to the given one ($n_t = n$) at the moment of the expiration of the settlement term. If $\Delta < 0$ it will happen earlier, if $\Delta > 0$ - after the given term.
3. IVP that are designed for the term of winning of block rooms (for 2 years) can last "eternally", if $\Delta \geq 0$ and $n \geq 1.2$.
4. If IVP and barrier pillars are designed for unlimited supporting of the main roof ($t = \infty$), and the factor of stock used in calculations $n = 1.3$, it is possible to declare with sufficiently great probability that these pillars will stand "eternally".

Presented by E. Reinsalu
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