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ANALYSIS OF THE ROOF AND PILLAR DESIGN IN ESTONIA'S OIL SHALE MINES

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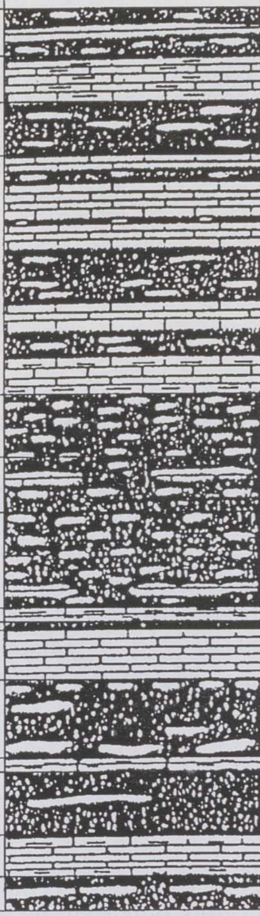
This paper analyses the pillar and roof design in Estonia's oil shale mines, where the roof-and-pillar mining is used. Numerical modeling was performed by the FLAC-program, using Mohr-Coulomb's failure criterion, average strength and elasticity parameters. The methodology for rock mechanics modeling in data limited conditions was exploited. Analysis showed that the roof calculation method includes very large factor of safety. Tributary area method was used for pillar design. It is recommended to use a monitoring system for estimation the stability of a mining block. Performed analysis and recommendations enable to improve the underground design quality in Estonia's oil shale mines.

Introduction

The most important mineral resource in Estonia is a peculiar kind of oil shale. It is located in a densely populated and rich farming district. The structure of the productive oil shale bed makes the rocks more difficult to break from the total massive. This is also one reason why shearer mining has been shortly used. It is estimated that about 80-90 % of the total underground oil shale production is obtained by room-and-pillar method. The method is cheap, highly productive, easily mechanizable, and relatively simple to design.

The objective of design is to extract the maximum amount of oil shale that is compatible with safe working conditions. For the underground constructions design, the instruction for Estonia's oil shale mines was elaborated [1, 2]. Instruction contains the calculation methods for the optimum parameters of the roof, pillars and support which is based on the long-term investigations in the oil shale mines.



Seam	Lithology	Thickness, m	Height from A seam, m	Observation
H		0.38	5.56	Immediate roof
H/G		0.26	5.18	
G		0.33	4.92	
G/F		1.43	4.59	
F_2		0.36	3.16	
F_1		0.35	2.80	Commercial oil-shale bed
E		0.53	2.45	
E/D		0.10	1.92	
D		0.10	1.82	
D/C		0.22	1.72	
C		0.42	1.50	
C/B		0.12	1.08	
B		0.54	0.96	
B/A		0.16	0.42	
A		0.26	0.26	

Fig. 1. Schematic geological section of the commercial oil shale bed and immediate roof

This paper analyses the underground construction calculation methods which enable to improve the underground design quality in Estonia's oil shale mines. We shall consider mine pillar and roof design, but similar scruting should be applied to the monitoring system.

It is important to note that despite relative simplicity of the structure, and detailed knowledge of rock behavior obtained over the past few years, pillar and roof design have changed very little during the present century.

Geology

The commercially important part of oil shale stretches from west to east for 200 km (from Rakvere to Luga), and from north to south for 30 km (from the coast of Gulf of Finland up to the shore of Lake Peipsi). The oil shale bed lays in a form of a flat bed having a small inclination (2-3 m per km) in a southern direction. The depth of the oil shale bed varies: at the northern border of the field, the bed lies under the Quaternary sediments, at the southern rim - even at the depth of 100-150 m. The thickness of the commercial oil shale bed decreases somewhat westward and southward from the central part of the deposit. The reserves of oil shale in Estonia are estimated approximately at 4 thousand million tonnes [3].

The oil shale layers occur among the limestone interlayers in Kukruse Regional Stage of the Middle Ordovician. It is a stratified sedimentary rock, rich in organic matter (15-46 % kerogen, 26-57 % carbonate, 18-42 % clastic materials). Stratigraphic column is represented in Fig. 1. The commercial oil shale bed consists of six oil shale layers which are specified from bottom to the top by the following indexes: A, B, C, D, E, F_1 and limestone by B/A, C/B, D/C, E/D, F/E. Immediate roof is represented by oil shale (F_2, G, H) and limestone (G/F, H/G) layers. The oil shale layers located higher than F_1 are not exploited. The main roof consists of carbonate rocks of different thickness.

The characteristics of the certain oil shale and limestone layers are quite different. The compressive strength of oil shale is 20-40 MPa and that of limestone is 40-80 MPa. The volume density is respectively 1.5-1.8 Mg/m^3 and 2.2-2.6 Mg/m^3. The strength of the rocks increases in the southward direction. The calorific value of the dry oil shale is about 7.5-18.8 MJ/kg according to the layer and the area in the deposit.

Oil Shale Mining

In Estonia's oil shale mines the room-and-pillar mining system is used. The field of an oil shale mine is divided into panels, which are subdivided into mining blocks, each approximately 300-350 m in width and from 600-800 m in length. The oil shale bed is embedded at the depth of 40-75 m. Its height corresponds to the thickness of the commercial oil shale bed, approximately 2.8 m. The width of the room is determined by the stability of the immediate roof. It is very stable when it has a dimension of 6-10 m. In this case, the immediate roof must still be supported by bolting. Actual mining practice has shown that pillars with a square cross-section suit best. The cross-sectional area of the pillars is 30-40 m^2, depending on the depth of the oil shale bed.

The main operations carried out in rooms include bottom cutting, drilling of blastholes, blasting, loading of oil shale and supporting. It is important to note that organization of work in a stope is rather complicated, especially due to the great volume of blasting operations. A work cycle lasts for over a week.

Roof Stability and Calculations

Long-Term Strength of the Rocks

The long-term strength of the rocks in Estonia's oil shale mines is presented by the following Formula [1, 2]:

$$R_t = K_t R_0 \tag{1}$$

where R_t - rock strength at the moment t;
R_0 - rock strength at the moment $t = 0$;
K_t - long-term strength coefficient.

The long-term strength coefficient is expressed by empirical formula [1, 2]:

$$K_t = \alpha + \beta \left(\frac{1}{1+t} \right)^m \tag{2}$$

where t - life-time of the construction;
α, β, m - empirical coefficients ($\alpha = 0.44$, $\beta = 0.56$, $m = 0.6$).

The values of the empirical coefficients α, β and m are the same for the roof and pillars. As it is visible from geological section (Fig. 1), the structure of the immediate roof and pillars is different. Consequently, the above-mentioned coefficients must be different, too. Analysis of the roof and pillar calculation scheme in Estonia's oil shale mines enables us to determine this difference.

Roof Stability

The roof of the Estonia's oil shale mines is represented of the layers of different rocks, thickness and properties (Fig. 1). The roof calculation is based on an original idea and presented by the following formula [4, 5]:

$$\frac{f_t}{f_0} = \frac{R_t^2}{R_0^2} = \frac{L_t^4}{L_0^4} \tag{3}$$

where f_t - roof sag at the moment t;
f_0 - roof sag at the moment $t = 0$;

L_t - span length at the moment t;
L_0 - span length at the moment $t = 0$.

Using Eqs. (1) and (3), it is possible to get a formula for immediate roof calculation [1, 2]:

$$L_t = K\sqrt{\frac{K_t}{n}L_0} \quad (4)$$

where $L_0 = K + MH_k$;
K and M - rock constants;
H_k - thickness of the carbonate rocks on the overburden (main roof);
n - factor of safety;
k - coefficient, depending on the stability of the roof; existence of the karst, type of the support system and importance of the surface object.

By the instruction, the factor of safety for the immediate roof equals to 1.8 (lifetime two months) [2]. The same parameter for the pillar is 1.2. Analysis showed that the factor of safety for the roof is very large. It means that the factor of safety includes a set of unknown factors: the inexactitude of the long-term strength of the roof rocks and the strength of rocks, depending on the depth of the excavation. Consequently, the coefficient of long-term strength and rock strength gradient demand supplementary investigations.

Pillar Stability and Calculations

Pillar Design

Pillar design ought to be a matter of matching pillar strength against pillar loading conditions to come up with dimensions that will cause the pillar to behave as required - to stand forever, or for a limited time, or to fail in a controlled manner.

Pillar design in Estonia's oil shale mines is based on the average pillar stress, and is known as the tributary area method. This assumes that each of the pillars left during excavation supports all the overlying strata that are "tributary" to their location. Pillar failure occurs when these stresses exceed the compressive strength of the pillar rocks. Here, the Sheviakov's and Turners' calculation scheme was used [6]. Obviously it would be not correct to design for tributary load on pillars. It is of great importance to remember that the load on real pillars is not some "average" figure, but that is controlled, in part, intentionally or otherwise, by the arching or bridging mechanism.

Pillar Loads

Pillar loads depend on the width of the mining block, leading to the concept of the critical width. The critical width is the greatest width that the rock above the mine can span before its failure or, if there are pillars, the width to which we must mine before the pillars accept the full weight of the overlying materials [6, 7]. Many theories available offer an excellent explanation for this process and help to calculate the critical width. Borissov's calculation scheme describes the behavior of the overburden rocks in the conditions of Estonian oil shale mines adequately. It can be expressed by the following Equation [6]:

$$\frac{L}{H} \geq 0.8 - 1.0 \tag{5}$$

where L - width of the mining block;

H - thickness of the overburden rocks.

In fact, the best indicator of critical width in a given situation will be provided by the records of failures and surface subsidence from measuring roof-to-floor convergence in the mine. It is important to notice that pillar loads vary from place to place within a mining block, depending mostly on the extent of the roof sags at each place.

Two different assumptions regarding the pillar loads in a mining block are represented here:

- A roof will sag closest to the center of the mining block, where higher loads are likely to occur. Accordingly, the vertical stress on the pillar predominates close to the center of the mining block.
- On the pillars, both the normal and shear stresses predominate towards the margins of the mining block.

Numerical Modeling

To determine the loads and stability of the pillar, the computational method of stress analysis was employed. In this study, the two-dimensional Fast Lagrangian Analysis of Continua (FLAC. Version 3.22) [8] was used. FLAC has several built-in material behavior models and is particularly suitable for modeling non-linear, large strain and physically unstable continuous systems. All the calculations were performed in the Laboratory of Rock Engineering of the Helsinki University of Technology.

The problem of the pillar load and stability in a mining block is fundamentally three-dimensional. However, it is reasonable to use the two-dimensional continuous model in the analysis. Though this simplification leads to some inaccuracy, the error is generally conservative. The model represents a vertical cross-section of a mining block by the room-and-pillar system, and it is meant for determining the load and deformation in the roof and pillars. The vertical axis is the only axis of symmetry that enables simplification of further modeling. In a conceptual model, both the vertical and the bottom boundary were prevented from displacing laterally.

In Estonian oil shale mines, the pillars and the roof are non-homogeneous and structurally complicated. They consist of the oil shale and limestone layers of different properties and thickness. In the calculations, average rock properties were used [9]. The strength and elasticity parameters for oil shale and limestone were derived from the tests conducted by Reinsalu [10]. The rock mass was assumed to behave as an elastoplastic material with the Mohr-Coulomb yield criterion. Here, the methodology for rock mechanics modeling in data limited conditions was used [11].

Figure 2 shows the vertical and horizontal displacement contours in the pillars and in the vicinity of roof and floor under overburden loading within the mining block. Our analysis shows that the roof sags closest to the center of the mining block and higher vertical loads are likely to occur there. In the pillars, both the vertical and horizontal displacements

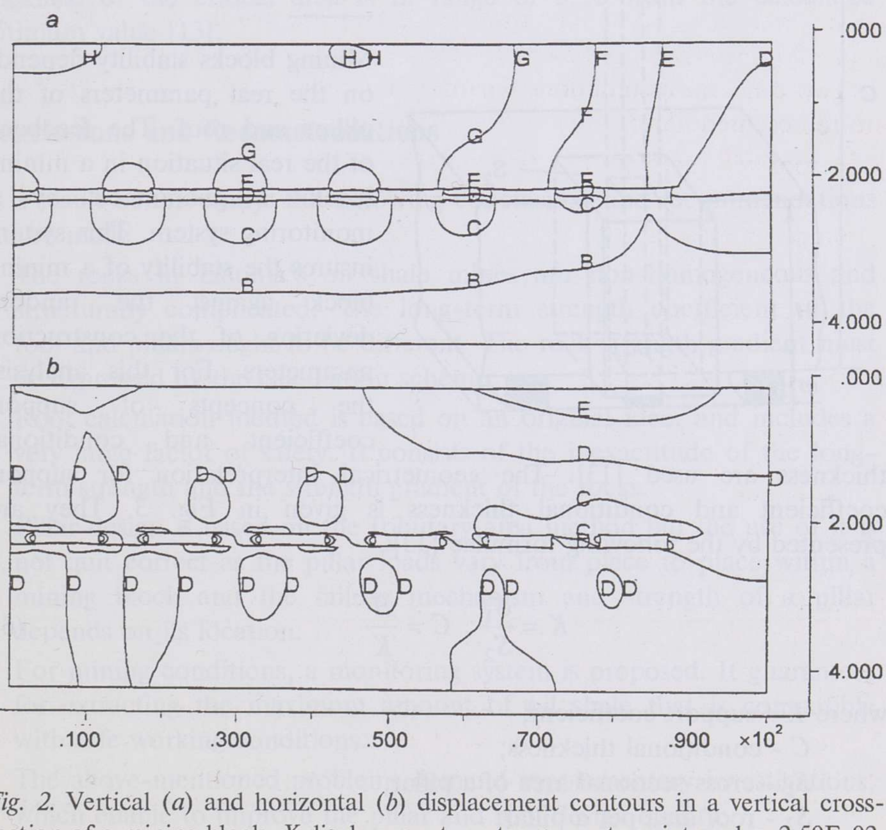


Fig. 2. Vertical (*a*) and horizontal (*b*) displacement contours in a vertical cross-section of a mining block. *X*-displacement contours: contour interval = 2.50E-02; *C*: -2.500E-02; E: 2.500E-02

occur towards the margin of the mining block. In consequence, the vertical and horizontal stresses appear there.

The investigations showed that the type of failure mechanism depends on the stress field at the boundary of a pillar [12]. By the vertical stress field, localization of plastic strain occurred with the inclined band, under vertical and horizontal stresses - with vertical band. A pillar is stronger under the vertical stress field. Consequently, the strength of a pillar in the mining block depends on the locality of one.

Monitoring of the Roof and Pillars Parameters

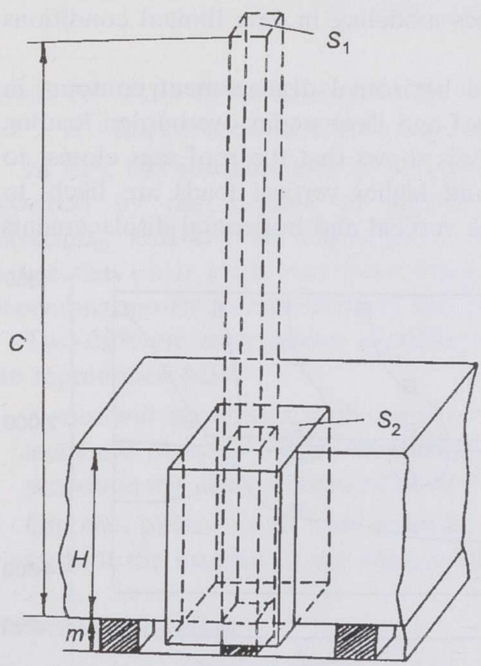


Fig. 3. Geometrical interpretation for support coefficient *K* and conditional thickness *C*: *m* - thickness of the commercial oil shale bed; *H* - thickness of the overburden rocks; S_1 - cross-sectional area of the pillar; S_2 - roof area per a pillar

←——

Mining blocks stability depends on the real parameters of the pillars and roof. The feedback of the real situation in a mining block is guaranteed by a monitoring system. This system insures the stability of a mining block against the random deviation of the construction parameters. For this analysis, the concepts of support coefficient and conditional thickness are used [13]. The geometrical interpretation for support coefficient and conditional thickness is given in Fig. 3. They are presented by the following formulae [13]:

$$K = \frac{S_1}{S_2}; \; C = \frac{H}{K} \qquad (6)$$

where *K* - support coefficient;

C - conditional thickness;

S_1 - cross-sectional area of a pillar;

S_2 - roof area per a pillar;

H - thickness of the overburden rocks.

In the three-dimensional case, the critical width transforms to the critical area. The average support coefficient and conditional thickness for a critical area can be expressed by the following Equation [13]:

$$K_c = \frac{\sum S_{1_i}}{\sum S_{2_i}}; \; C_c = \frac{H_a}{K_c} \tag{7}$$

where H_a - average thickness of the overburden rocks for critical area;
S_{1_i} - cross-sectional area of the i-th pillar;
S_{2_i} - roof area per the i-th pillar;
K_c - support coefficient for critical area;
C_c - conditional thickness for critical area.

Analysis showed that the critical area is better related to average conditional thickness than the average support coefficient. It suits for stability analysis [13]. By this method, the average conditional thickness of the critical area must be determined for all positions inside a mining block. The stability of the pillars and roof, and the extraction of the maximum amount of oil shale area is insured, if the average conditional thickness of the critical area is in range of 5 % from the calculated optimum value [13].

Conclusions and Recommendations

As a result of this study, the following conclusions and recommendations can be made.

1. The rocks in Estonia's oil shale mines are non-homogeneous and structurally complicated. The long-term strength coefficient of the roof and pillars ought to be different. The rock strength gradient must be expressed by the calculation scheme.
2. Roof calculation method is based on an original idea, and includes a very large factor of safety. It consists of the inexactitude of the long-term strength and the strength gradient of the rocks.
3. Pillar design is based on the tributary area method but the use of it is not quit correct as the pillar loads vary from place to place within a mining block and the failure mechanism and strength of a pillar depends on its location.
4. For mining conditions, a monitoring system is proposed. It guarantees for extracting the maximum amount of oil shale that is compatible with safe working conditions.
5. The above-mentioned problems demand supplementary investigations, which enable to improve the pillar and roof design quality.

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