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MINING BLOCK STABILITY ANALYSIS FOR ROOM-AND-PILLAR MINING WITH CONTINUOUS MINER IN ESTONIAN OIL SHALE MINES[*]

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Without progressive technology to make mining economically viable, this industry, which provides a significant contribution to Estonia's economy, can no longer exist. This paper presents a proposal for a comprehensive mining system. Determination of the pillar and roof optimum parameters for new mining technology with continuous miner was the main aim of the present work. The conventional calculation formulas and conditional thickness methods were used to determine the room-and-pillar mining system parameters, which guarantee a long-term stability. The calculation methods used gave excellent results.

Introduction

The most important mineral resource in Estonia is a specific kind of oil shale. About 99% of electric and a large share of thermal energy are being generated from oil shale. The importance of oil shale production for the development of Estonian economy cannot be overestimated. It is estimated that about 80–90% of the oil shale total underground production is obtained by room-and-pillar (RAP) method with blasting. The method is cheap, highly productive and relatively simple to apply. However, some problems related are as follows:

- Decreasing amount of oil shale production (about 50%)
- Old technology and old-fashioned mining machinery (low extraction factor)
- Mining block stability (collapse and surface subsidence)

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The new RAP mining method with continuous miner gives the greatest extraction factor, high productivity and leaves off-grade rock mass in the underground mined-out areas. As oil shale deposit is located in a densely populated and intensely farmed district, the mining system must guarantee a long-term stability of the pillars and roof.

Geology

The commercially important oil shale bed is situated in the northeastern part of Estonia. It stretches from west to east for 200 km, and from north to south for 30 km. The oil shale bed lays in the form of a flat bed having a small inclination in southern direction. Its depth varies from 5 to 150 m. The oil shale reserves in Estonia are estimated to be approximately four billion tons.

The oil shale seams occur among the limestone seams in the Kukruse Regional Stage of the Middle Ordovician. The commercial oil shale bed and immediate roof consist of oil shale and limestone seams. The main roof consists of carbonate rocks of various thicknesses. The characteristics of certain oil shale and limestone seams are quite different. The compressive strength of oil shale is 20–40 and that of limestone – 40–80 MPa. The strength of the rocks increases in the southward direction. Their volume density is 1.5–1.8 and 2.2–2.6 Mg/m^3, respectively. The calorific value of dry oil shale is about 7.5–18.8 MJ/kg depending on the seam and location in the deposit.

Continuous Miner – Non-Explosive Rock-Breaking Technology

The continuous miner (CM) system is the first choice for all RAP development operations in the underground coal markets of the USA, Australia, South Africa and the UK. CMs have been introduced and are operating successfully in Russia, China, Japan, Zimbabwe, France, Italy, Mexico and Norway. At present there are almost 2,000 CMs operating in over fourteen countries worldwide.

The growth of CM systems with rubber-tyre shuttle car and mobile bolting equipment was rapid. CMs are capable to mine seams of the thickness from 0.9 to 6.0 m. Cutting up to 6.0 m has been carried out at Gloria, Khutala and Matla in South Africa. In most cases in room and pillar sections one continuous miner and two shuttle cars (short distances of 50–400 m) are used for mineral transport and discharge onto a panel belt conveyor [1].

CM operations keep playing a major role in the underground mining industry. Estonian oil shale industry stands at the beginning of the introduction of modern fully-mechanized CM systems, which will dramatically increase productivity and safety in the underground mines.

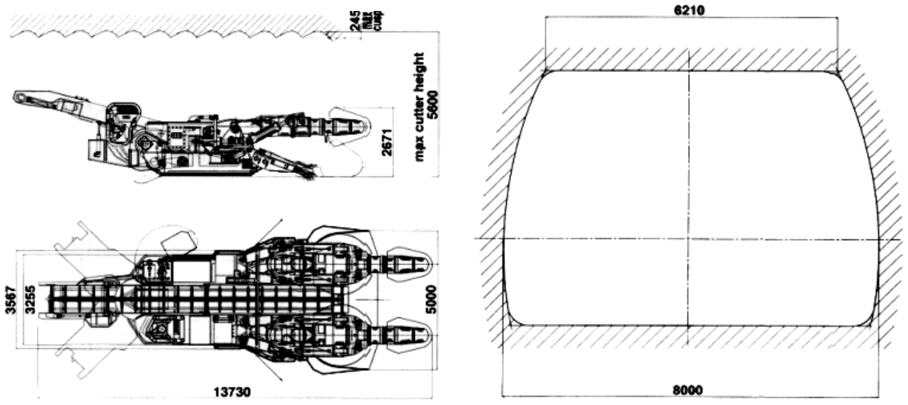

Fig. 1. CM Dosco TB2500 with twin cutting booms

Dosco CM (Fig. 1) is a machine designed for rapid entry development, integrating cutting, loading, material handling and operation ergonomics. Drum and gathering head extensions enhance clean-up operations and maneuverability when changing the place. The design of cutting heads ensures a perfectly flat floor, resulting in longer life of the wheel units of supporting shuttle cars. The machine is capable of cutting almost 8 m (26 ft) wide and to 6 m (19 ft 6 ins) high from a single position, yet can operate within 6-m (19 ft 6 ins) width and 2.6-m (8 ft 6 ins) height when required.

Current and New Mining Systems

In Estonian oil shale mines the RAP mining system with blasting is used (Fig. 2). It gives the extraction factor about 80%. The field of an oil shale mine is divided into panels, which are subdivided into mining blocks, approximately 300–350 m wide and 600–800 m long each.

A mining block usually consists of two semi-blocks. The oil shale bed is embedded at the depth of 40–70 m. The height of the room is 2.8 m. The room is very stable when it is 6–10 m wide. In this case, the bolting must still support the immediate roof. The pillars in a mining block are arranged in a singular grid. Actual mining practice has shown that pillars with a square cross-section (30–40 m^2) suit best. A work cycle lasts for over a week.

The area mined by RAP method reaches 100 km^2. It has become apparent that the processes in overburden rocks and pillars have caused mining block collapses accompanied by significant subsidence of the ground surface. Up to the present, 73 failures in Estonian oil shale mines have been registered, which make up 11% of the total number of mining blocks and 3% of the mined-out area. It is clear that the problems of the mining block stability are most topical.

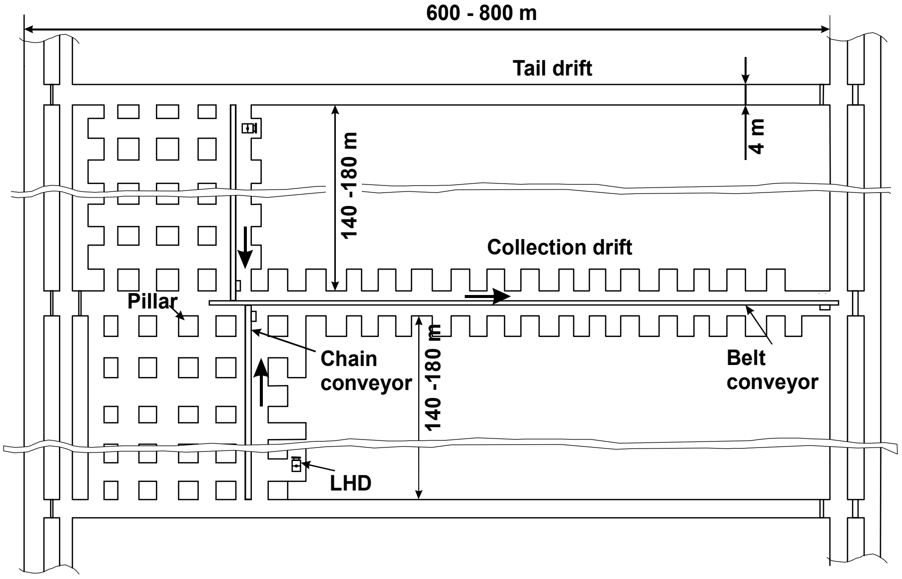

Fig. 2. Schematic layout of RAP mining in Estonian oil shale mines with blasting

Double-face-longwall mining with blasting, used in the then Leningrad oil shale minefields at the end of the 1970s [2], served as the background of the new RAP mining method with CM (see Fig. 5 below).

Analysis showed that the new method gives the greatest extraction factor (up to 90%). When using this mining system, the main and immediate roofs are supported by pillars of different cross-section area, but bolting must still support the immediate roof. From the environmental aspect it is very important to control the main roof to guarantee mining block stability for a long time without collapses of pillars and surface subsidence.

Design of the Pillar and Room Parameters

The critical width of the immediate and main roofs is determined in *in situ* conditions in Estonian oil shale mines. The critical width is the greatest width that the rock above the mine can span before its failure [3]. It is estimated that at the first collapse of the main roof the height of the rocks damaged reaches 11.6 m.

On the other hand, the actual parameters of the roof and pillars depend on the applied technology and quality of the mining works. Investigation has shown that using CM, the random deviation of the actual pillar and room sizes from the designed ones is less than ± 0.2 m. This factor is taken into consideration at designing pillars and room.

Room Sizes and Technological Requirements

The influence of random deviations of the actual room sizes (Table 1) on the stability of the immediate and main roofs is insignificant and not considered in calculations. Investigation showed that the safety factor of the calculated room dimensions (8 and 28 m) is big enough. Previous experiences in Estonian oil shale mines have shown that these values guarantee long-term stability of the rooms.

According to the instruction for Estonian oil-shale mines [4], using standard formulas the values of dependence of immediate roof critical width (IRCW) on geological conditions (k_p; k_0) and on pillar arrangements in mining block are easy to determine (Table 2).

Table 1. **Roof and Room Dimensions in Estonian Oil Shale Mines**

Roof type	Roof thickness, m	Roof critical width, m	Room width (designed), m
Immediate roof	3–4	12–15	8
Main roof	35–45	45–60	–
Main roof (up to the height of 11.6 m) L_m	11.6	35–39	28

Table 2. **IRCW and Room (*A*; *b*) Dimensions Depending on Geological Conditions (k_p; k_0) and on Arrangements of Pillars in Mining Block for the Case of the Furure *Ojamaa* Mine Field**

Item	k_p/k_0							
	1/1	1/0.80	0.85/1	0.85/0.80	0.70/1	0.70/0.80	0.55/1	0.55/0.80
Rectangular-grid pillars								
IRCW, m	13.7	10.9	11.6	**9.3**	**9.6**	7.7	7.5	6
A, m	11.1	8	8.4	**7**	**7.5**	6	5.3	4.5
b, m	8	7.5	8	**6.1**	**6**	4.8	5.3	4
T-grid pillars								
IRCW, m	13.7	10.9	11.6	9.3	9.6	**7.7**	**7.5**	6
A, m	11.5	10.5	11.4	8	8.5	**6.1**	**6**	5
b, m	10.5	7	7	7	7	**6.1**	**6**	4.5
Rib-pillar mining								
IRCW, m	13.7	10.9	11.6	9.3	9.6	7.7	**7.5**	**6**
A, m	13.7	10.9	11.6	9.3	9.6	7.7	**7.5**	**6**

The parameters k_p and k_0 take into account the influence of roof cracks (k_p) and distances to karsts (k_0) on the room stability. In ideal conditions $k_p = k_0 = 1$. If the distance to karsts is ≤ 60 m, then $k_0 = 0.80$. Parameter k_p depends on the immediate roof stability: in the case of high stability $k_p = 1$; average $k_p = 0.85$; and low stability $k_p = 0.7$; the roof is unstable when $k_p = 0.55$. For Dosco TB2500, minimal room sizes must be ≥ 6 m. In the case of complicated geological conditions, Table 2 gives minimal requirements for using CM mining method. For example, if the immediate roof stability is average (k_p = 0.85) and the distance to the karsts is ≤60 m (k_0 = 0.80), IRCW = 9.3 m, $A_{\min}$ = 7 m, and $b_{\min}$ = 6.1 m (pillars on rectangular grid).

Pillar Dimensions

To determine the bearing capacity of the pillars, the empirical formula developed at the Institute of Mining Survey (IMS), St. Petersburg, has been accepted as the calculation method.

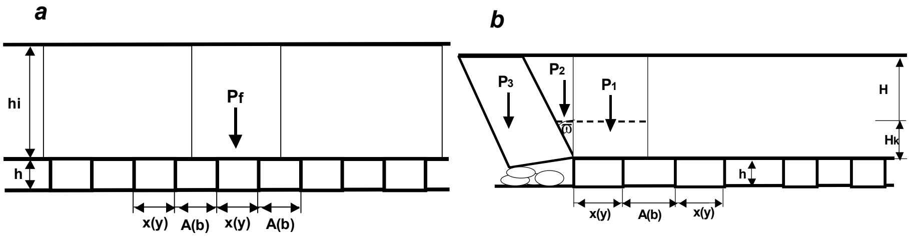

Fig. 3. Load distribution on intrablock (*a*) and barrier (*b*) pillars: h – height of the room; H – depth of excavation; h_i – thickness of the immediate roof; H_k – thickness of the covering carbonate rock mass; P_f; P_1; P_2; P_3 – loads on the pillars

The basic concept of the IMS method is that two features of strength characterize the rock pillar: basic and stabilized strength [5, 6]. Basic strength characterizes rocks at fast loading, e.g. at pressure testing. Under constant pressure, the current strength of rock decreases, and in some time it will equal the stabilized strength. This perception of rock behavior complies with the concept of material creep, a notion in strength of materials. Unfortunately, according to this approach the pillar failures calculated accurately are anomalies.

In the case of CM, cross-section area of a pillar must be less than in the case of RAP mining with blasting, by ~10–14%. Intrablock pillars in complex work with immediate roof anchor bolting are used to support immediate roof within the limits of room sizes (*A* or *b*).

Actual load P_{f1-2} on an intrablock pillar can be determined (Figs 3*a* and 4*a*) using Formulas (1)–(3) [7].

As for intrablock rectangular pillar dimensions,

$$y = \frac{nb(A+x)H\gamma}{k_k x R_t - n(A+x)H\gamma} \tag{1}$$

As for rib-pillar dimensions,

$$x^2 + \left[\frac{7}{3}h - \frac{nHhk_s\gamma}{0.3R_t}\right] \times x - \left[\frac{0.5nHhk_s\gamma}{0.3R_t}(B + l_0 + Htg(\omega))\right] = 0 \tag{2}$$

where $k_s = (b_0 + L_0)/L_0$.

As for intrablock square pillar dimensions,

$$x^3+\left[2.33h-\frac{nHh\gamma}{0.3R_t}\right]\times x^2+\left[\frac{nHh\gamma\times(A+b)}{0.3R_t}\right]\times x-\frac{nAbHh\gamma}{0.3R_t}=0 \tag{3}$$

where x and y are pillar dimensions, m;
A and b are room sizes, m;
H is thickness of the overburden rock, m;
h is height of the pillar, m;
γ is overburden rock average density ($\gamma = 0.025$ MN/m^3);
k_k is factor of the pillar form;
n is the given factor of pillar safety;
k_s is factor of the pillar easing (attenuation).

Analysis

The calculations are performed considering the conditions of the future *Ojamaa* mine, where excavation depth is 22–35 m, and thickness of the commercial oil shale bed 2.8 m (complex A–F_2), using a variant of 4.5-m extraction (complex A–G/H). The length of the intra-block pillar (pillar 3, schemes I–III) is constant (50 or 150 m), which is determined by technology. Minimum dimension of a pillar (pillar 4, scheme I) is limited and equals 2-3 m, depending on scale factor and depth [4]. The calculation results are presented in Table 3, the schemes are illustrated by Fig. 4.

Table 3. **Pillar Dimensions and Chamber Parameters for Different Schemes**

Legend	Scheme			RAP mining + blasting
	I	II	III	
	Pillar sizes $Y \times X$ (formula number), m			
Pillar 1	100 × 5			
Pillar 2	50 × 5			
Pillar 3	50 × 5	150 × 3.5		
Pillar 4	3 × 3	24 × 5	8 × 7	6 × 6
Pillar 5	9 × 6			
Room size A, m	7.3	11		7.5
Room size b, m	7.3	7		7.5
h[*1], m	4.5 (A–G/H)			
L_m, m	28	–	–	–
Extraction, %	84–89[*2]	78–80	80–82	77–82[*3]

[*1] Height of oil-shale layer complex.
[*2] Depends on the pillars' arrangement in a mining block.
[*3] Depends on the excavation depth H.

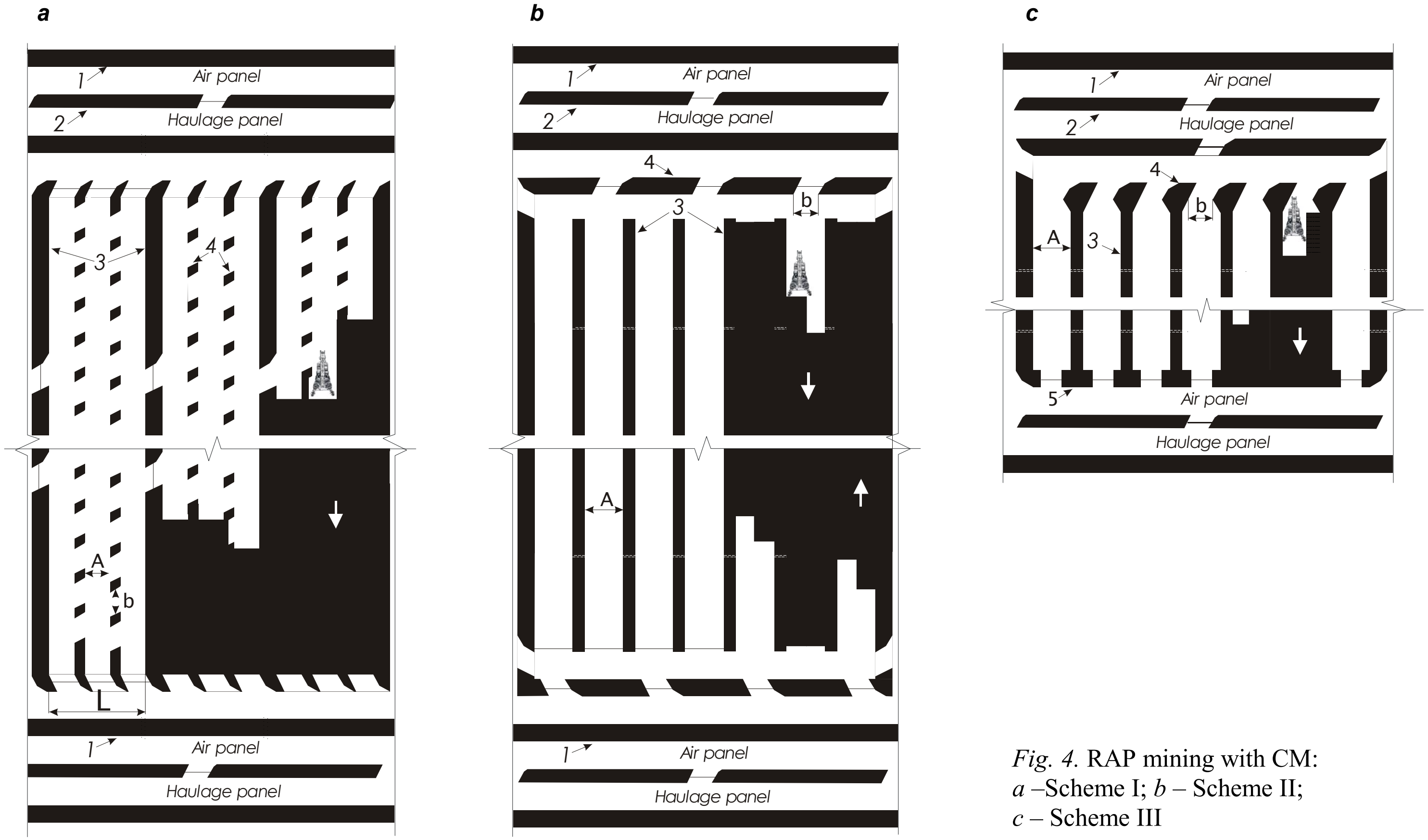

Fig. 4. RAP mining with CM:
a –Scheme I; *b* – Scheme II;
c – Scheme III

For stability analysis and monitoring the concept of critical width, methods of support coefficient, conditional thickness and sliding rectangle suitable for modeling on PC were used [8].

The critical width for Estonian oil shale mines is presented by the following formula [9, 10]:

$$L > 1.2H + 10 \tag{4}$$

In the three-dimensional case, the critical width transforms into the critical area. The average support coefficient and conditional thickness for a critical area can be expressed by the following equation [11, 12]:

$$K_C = \Sigma S_{pi}/\Sigma S_{ri};\ C_C = H_a/K_C \tag{5}$$

where K_C is support coefficient of the critical area;

C_C is conditional thickness of the critical area, m;

S_{pi} is cross-section area of the i-th pillar, m^2;

S_{ri} is roof area per the i-th pillar, m^2;

H_a is average thickness of the rocks covering the critical area, m.

Conditional thickness represents the height of a prism whose cross-section equals the pillar cross-section area. Consequently, conditional thickness is related to the load on a pillar. If the load on pillars is too much, a sudden failure is likely. The average conditional thickness of the critical area must be determined for all positions inside a mining block. For that purpose the sliding rectangle method is used. The method suits for stability analysis, failure prognosis and monitoring.

As one can see from Table 2, the arrangement of pillars in a mining block takes into account the influence of room sizes on the immediate roof stability. In this work pillars on T-grid arrangement and rib-pillar mining were used as basis for the variants under analysis.

Scheme I (Fig. 5) can be considered the dominant method (by the extraction factor). However, the conclusions can be made only basing on actual tests under *in situ* conditions.

Scheme I

Room and pillar parameters have been calculated basing on the scheme of overburden load distribution on different pillars (Fig. 5).

Rib-pillar (Table 3, pillar 3; and Fig. 4*a*) works as an intra-block pillar. Intra-room pillar (Table 3, pillar 4; and Fig. 4*b*) is left to support immediate roof only (when h = 2.8 m) or near the karst area to increase the main roof stability (when h = 4.5 m – up to the main roof).

Investigation showed that in this case intra-block pillar dimensions guarantee their long-term stability and exclude the collapse of the mining block. Therefore, the submitted variant can give extraction factor up to 84–89%.

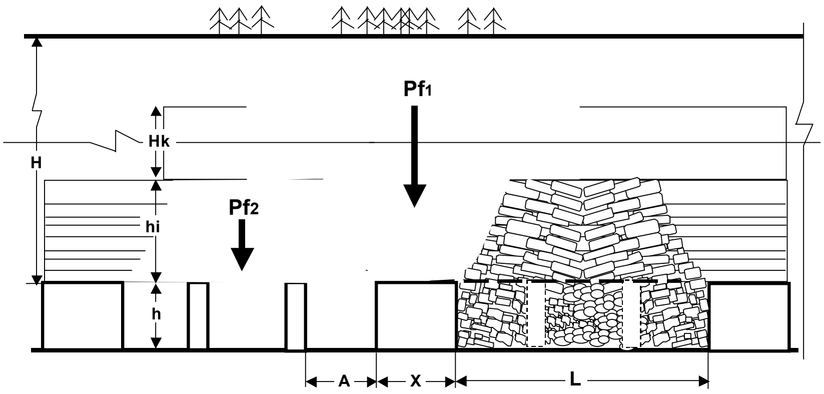

Fig. 5. Scheme I: overburden load distribution on different pillars

Schemes II and III

The values of room and pillar parameters of these variants (see Table 3) have been calculated according to the scheme of overburden load distribution on different pillars presented in Fig. 3. Pillars No. 4 (Figs 4*b* and 4*c*) serve to support entries, and rib-pillar (Table 3, pillar 3; Figs 4*b* and 4*c*) works as an intra-room pillar.

Schemes II and III provide extraction factor 78–80 and 80–82%, respectively. The first variant requires driving two additional entries at each of two sides, but the second one requires only one (Figs 4*b* and 4*c*). Obviously, Scheme III is better than Scheme II.

Comparison of the Presented Variants

For better presentation of the offered schemes it will be best to compare them with RAP mining method with blasting used in Estonian oil shale mines. For this purpose the values of room and pillar parameters were calculated (see Table 3). In ideal conditions RAP enables 78–82% extraction.

The analysis showed that RAP method with CM (Scheme I) gives the greatest extraction factor, and theoretically excludes spontaneous collapses. In the case of long-term main roof control, RAP method with blasting gives the greatest cross-section areas of pillars and decreasing of extraction factor. However, in the case of CM, the use of special main roof control increases extraction factor up to 89%, i.e. by about 10%.

Some Technical and Technological Recommendations to Improve Roof Stability

Satellite Bolters

Roof support will be achieved through the use of roof bolts. For roof bolting in entries a twin-boomed roof-bolter is recommended. Mining machine must enable simultaneous bolting and cutting to provide maximum productivity and entry-advance rates. The main frame must be specially designed for roof-bolting patterns significantly improving roof control, reducing bolt-to-face distances and exposure of unsupported roof. The combination of Dosco continuous miners and roof drills makes an unbeatable match for reliability and availability, thus reducing downtime and operating costs.

Back-Filling and Reasons
By placing back-fill into the mined-out stalls, structural integrity of the pillars is greatly increased. The fill material becomes compacted and exerts a confining force on the remaining pillars, increasing their strength. This is particularly important close to the entries where personnel are located. If there is sufficient waste material to allow total back-filling, the pillars between face openings may have a smaller width. This will give higher recoveries and improved profit margins for the mine. In the case of selective mining we do not have a sufficient limestone rock mass for total back-filling.

Another reason to consider full back-filling falls directly under the wider economic considerations of this plan: disposal of solid wastes. If imported solid wastes can be mixed into the fill to provide a rapid-setting and low permeability material, this provides a means of generating additional revenue for the mining company. However, for the present it is assumed that the fill material required for seals will be not provided from the limestone rock mass produced from rooms and development drifts (in the case of selective mining).

Critical Point

Estonia's oil shale mining industry is approaching a critical point. Without a progressive technology to make mining economically viable, this industry, which provides a significant contribution to Estonia's economy, can no longer exist. This paper presents a proposal for a comprehensive mining system capable to solve technological problems of existing mining systems *via* their modifications and improvements. There are, however, other factors that must be considered to insure that oil shale mining retains its important position in Estonia's economy. These non-technical factors have more to do with public and private perceptions than with technological difficulties.

On the other side, the oil shale mining workforce is aging, and young technically trained workers must see that there is a future in oil shale mining, a future that will allow them a stable life in the area where they grew up. Many young workers will move elsewhere to improve their employment opportunities. *Eesti Põlevkivi* (*Estonian Oil Shale*) mining company must be willing to take the financial risk associated with the purchase, development, and testing of new mining systems. The co-operation of all interested parties will help to reduce the risks and insure the involvement of the mining concern. The railroads have a major stake in the survival of oil shale mining, because of the revenues generated from the transport of this commodity, and the economic benefits to the people through the transportation industry are significant.

All of these parties stand to benefit greatly from co-operation in the effort to develop the mining systems of the future.

Conclusions and Recommendations

In the future, some specific connected problems, namely transportation and ventilation, will be solved in detail.

The layout of mining fields is highly influenced by the production and transportation system. The main transport devices in oil shale mines are belt conveyors, trains or underground trucks. The first ones are used today. It is obvious that they have low flexibility. The technology for shuttle cars has also been worked out. Underground tracks can be another alternative (when $L \leq 3000$ m). This system offers higher flexibility, but will cause problems concerning ventilation and transport (in the case of diesel machines). However, today other progressive decisions for integration of mining and continuous haulage systems are available, e.g. flexible conveyor trains (Joy Mining Machinery), full-dimension continuous haulage systems, bridge conveyor (Long-Airdox, Joy), and underground archveyor systems (Arch Technology Corporation).

Marissa Operating Unit of Peabody Coal Co. in southwestern Illinois employs three different haulage systems. Marissa pioneered one of those systems, the Flexible Conveyor Train, and Peabody has worked with Joy Mining Machinery to upgrade the continuous haulage system [13]. Coal mining in Southwest Virginia (USA) uses Archveyor Underground and bridge conveyor systems [14].

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

1. The problem of mining block stability and surface subsidence is very actual in a densely populated and intensely farmed district like NE Estonia.
2. The lifetime of pillars is calculated by conventional calculation formulas used in the case of Estonian oil shale mines. The conditional thickness method allows improving the quality of calculations and determining stable values of the pillar and roof parameters. The applied calculation method guarantees long-term stability of the room and pillars. Collapse of a mining block and ground surface subsidence are excluded.
3. Selective mining method allows using oil shale without additional costs for its preparation for power-generating plants.
4. New technology with flexible and mobile mining equipment allows decreasing the lifetime of the main roof support, reduction in the sizes of constructive elements, and, as a result, a decrease in oil shale losses in pillars is expected. Expenses are compensated by the economy gained from the rise in the labor productivity.

5. Non-utilizable waste in stockpiles is a potential problem in mine areas. Oil shale selective mining by LHD machines allows leaving off-grade rock mass in the underground mined-out area (in the rooms).
6. The improved method of main roof control is a guarantee of mining block stability for a long time excluding collapse of pillars and ground surface subsidence, both being most important from the environmental aspect.
7. The use of the new method enables to increase extraction factor from 77–82 to 84–89%.

In the future the main target would be feasibility study for acquiring new equipment and comparing of different technologies. The present work could be used as one part of the feasibility study.

Acknowledgements

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REFERENCES

1. *Mathur, R.B.* Technology for tomorrow and equipment selection for Indian coal mines // MPES 2002, Bouzov, Czech Republic, 9–11 September 2002. 2002. P. 143–148.
2. *Nikitin, O.* Monitoring and analysis of room-and-pillar mining with continuous miner in Estonian oil shale mines // 3rd Intern. Conf. “Environment. Technology. Resources”. Rezekne, Latvia, 19–21 June 2001. 2001. P. 116–121.
3. *Parker, I.* Mine pillar design in 1993: Computers have become the opiate of the mining engineers // Mining Engineering, London. 1993. July and August. P. 714–717 and 1047–1050.
4. Flow Sheet of Driving and Extraction in the Estonia Oil Shale Deposit by Using Mobile Face Haulage Units. – Moscow, 1988 [in Russian].
5. *Plahhov, A.V.* Drafting of Regulations for Protecting Structures and Natural Objects From Damaging Effects of Underground Mining Structures in the Baltic Oil Shale Deposit Area : Manuscript / ISM, St. Petersburg [in Russian].
6. *Reinsalu, E.* Stochastic approach to room and pillar failure in oil shale mining. Estonian Scientific Academy Edition : Technical Edition. 2000. Vol. 6, No. 3. P. 207–216.
7. *Undusk, V.S.* Pillars destruction in oil shale mines // Transact. Tallinn Technical University. 1990. No. 718. P. 31–40 [in Russian].
8. *Nikitin, O., Pastarus, J-R., Sokolov, P.* Monitoring and stability analysis in Estonian oil shale mining // 11th Intern. Congr. of the International Society for Mine Surveying, Cracow, September 4–9, 2000. 2000. P. 319–327.
9. Room, pillars and safety zones calculation methods for underground oil-shale mining. – Tallinn, 1997 [in Estonian].

10. *Stetsenko, V., Ivanov, G.* Prognosis of the time-depending roof displacements for different span lengths // Oil Shale / EstNIINTI (Information Series). 1981. No. 11. P. 13–18 [in Russian].
11. *Pastarus, J.* Study and analysis of the mining blocks situation in the mines of *Estonslanets* // Trans. Tallinn Polytech. Inst. 1982. No. 533. P. 3–14 [in Russian].
12. *Talve, L. G.* Check-up of real parameters of room-and-pillar mining in Estonian oil shale mines // *Ibid*. 1978. No. 451. P. 23–35 [in Russian].
13. *Sprouls, Mark W.* Continuous mining on the cutting edge // Coal Age. 1998. September 1.
14. *Holman, D., McPheterson, M.J., Loomis, I.M.* Underground thin-seam coal mining in Virginia / Virginia Center for Coal and Energy Research, report No. 99-01, July 1999.