IMPROVED METHOD OF PREDICTING LONG-TERM STABILITY OF THE MINING BLOCKS IN ESTONIAN OIL SHALE MINES

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Abstract
The paper deals with the methods of long-term stability prediction and monitoring of the room-and-pillar mining system. Conditional thickness method suitable for calculations considers only geometrical parameters of the roof and pillar. For practical application the factors influencing conditional thickness parameters (geological conditions, rock properties) were determined and classified. Prediction method allows determination of the location, area and time of the collapse in a mining block. The uncertainty in time is less than 10 % at the 95 % confidence level. The applicability of the prediction method by conditional thickness is demonstrated in theory and demands further adequacy analysis.

Keywords: conditional thickness method, influence factor, mining block, pillar, roof, stability.

1. Introduction
The mineral wealth of Estonia – oil shale - is located in a densely populated and rich farming district. It is known that the post-effects of mining may suddenly appear many years after the end of excavation. The post-technological processes of the underground mining have caused and will cause in the future a large number of technical, economical, ecological and juridical problems.

The first spontaneous collapse of the pillars and the surface subsidence in an Estonian oil shale mine took place on 1964. Up to the present, 73 collapses have been recorded on the area of 100 km².

Working out the mining block long-term stability prediction method by conditional thickness and determination of the factors influencing this process was the main aim of the present work.

For the analysis the concept of critical area, methods of conditional thickness and sliding rectangle were used (1, 2, 3). They suit for modeling on PC. The results are presented by conditional thickness contours, which allow determining collapse parameters in a mining block. The conditional thickness method does not take into consideration the geological conditions and rock properties. For practical application all factors influencing the parameters of conditional thickness are to be considered at modifying conditional thickness contours on a mining block map. In this case the mining blocks in different geological conditions are comparable and applicable for prediction of long-term stability. The preliminary calculation showed that the uncertainty in time does not exceed 10% at the 95 % confidence level.

The calculation method by conditional thickness is applicable in different geological conditions. The surface subsidence parameters will be determined by conventional calculation schemes.

2. Geology and mining
The commercially important oil shale bed is situated in the north-eastern part of Estonia. 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 at 4 thousand million tons.

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 the certain oil shale and limestone seams are quite different. The strength of the rock increases in the southward direction.
In Estonian 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, approximately 300-350 m in width and from 600-800 m in length each. A mining block usually consists of two semi-blocks. The oil shale bed is embedded at the depth of 40-70 m. The room is very stable when it is 6-10 m wide. The pillars in a mining block are arranged in a singular grid.

3. Theoretical background

For the analysis the concept of critical area, methods of conditional thickness and sliding rectangle were used (1, 2, 3). They suit for modeling on PC. The critical width is the greatest width that we must mine before the pillars accept the full weight of the overlying material. Conditional thickness represents the height of a prism whose cross-section equals the pillar cross-section area. It is presented by the following formula [1, 2]:

\[ C_0 = \frac{HS_r}{S_p} \]  

(1)

where \( C_0 \) – calculated conditional thickness, m; \( S_p \) – cross-sectional area of a pillar, \( m^2 \); \( S_r \) – roof area per pillar, \( m^2 \); \( H \) – thickness of the overburden rocks, m.

Unfortunately, the conditional thickness takes into consideration only geometrical parameters of the room and pillar: cross-sectional area of a pillar, roof area per pillar and thickness of the overburden rock. It is related to the load on a pillar. If the load is too much for the pillars, a sudden failure is likely. By the sliding rectangle method, the average conditional thickness of the critical area must be determined for all positions inside a mining block. The results are presented by conditional thickness contours. This is not applicable for practical purposes. The uncertainty in conditional thickness contours does not exceed 1.5 % at the 95 % confidence level.

The method of predicting mining block stability bases on the analysis of the conditional thickness contours on the map of a mining block. At calculations, the influence of geological conditions and rock properties on the stability of a mining block is to be considered. Elaboration of this method is cumbersome, time- consuming and demands exact knowledge about the processes in the rock massive and constructions. For practical application it is necessary to classify the factors influencing conditional thickness parameters. The influence on the pillars load or strength is caused from:
1. rock massive and barrier pillars;
2. rock fracture;
3. pillar size;
4. excavation depth;
5. tectonic jointing;
6. different cross-section area of the pillars.

The relationship between these factors is expressed by the following formula:

\[ C = C_0 \prod_{i=1}^{n} K_i \] 

(2)

where \( C \) – real conditional thickness, m; \( C_0 \) – calculated conditional thickness, m; \( K_i \) – influence factor; \( n \) – number of influence factors.

It is necessary to determine the value of each influence factor and modify the calculated conditional thickness by the formula 1. Only then the mining blocks subject to different conditions are comparable. The uncertainty in time of this method does not exceed 10% at the 95 % confidence level. The method demands supplementary investigation and determination of its adequacy in in-situ condition.
4. Influence factors

4.1. The influence of rock massive and barrier pillars on the load of the intra-room pillar
Towards the margin of a mining block, there appears a zone where the load on pillars is less than in the centre. It is related to the influence of the rock massive and barrier pillars (Fig.1).

![Figure 1. Geometrical interpretation of the influence zone in a mining block](image)

W – width of the mining block; L – length of the mining block; w – width of the influence zone.

Theoretical investigations and modeling on PC (FLAC-program) show that the influence zone of the barrier pillars and rock massive equals to the half of the critical width (4, 5).

\[ Z = \frac{L}{2} = \frac{1.2H + 10}{2} \]  \hspace{1cm} (3)

where \( Z \) – width of the influence zone, m; \( L \) – critical width, m.

The pillar load ratio in the influence zone is presented by the following formula:

\[ K_1 = \frac{w \tan \alpha}{H} \]  \hspace{1cm} (4)

where \( K_1 \) – pillar load ratio in the influence zone; \( w \) – pillar distance from the rock massive or barrier pillars, m; \( \alpha \) - angle of major influence, deg (\( \alpha = 55^0 \)).

Formula (4) is valid when the distance between the pillar and rock massive (barrier pillars) is in the range \( 0 < w < \frac{H}{\tan \alpha} \), beyond the limit \( K_1 = 1 \).

4.2. Pillar strength dependence on the fracture process (6)
Two-dimensional theoretical and numerical modeling was performed, based on the Mohr-Coulomb’s failure criterion. Towards the center of a mining block, the vertical load occurs on the top of the pillar, and the orientation of the fracture plane is inclined according to the Mohr-Coulomb’s theory. Towards the margin of a mining block, the inclined load occurs on the top of the pillar and the orientation of the fracture plane is vertical (Fig.2). The results of theoretical investigations and modeling on PC are close to those in in-situ conditions. The pillar is stronger under the first type of the stress state.
Uni- and bi-axial strength ratio of the pillar is (6):

\[ K_2 = \frac{1 + \sin \varphi}{\sin \varphi} \]  \hspace{1cm} (5)

where \( \varphi \) - internal friction angle, deg.

In the case of the compressional shear fracture (towards the center of a mining block) \( K_2 = 1 \), in the case of axial (towards the margin) \( K_2 > 1 \).

4.3. The influence of pillar size on the pillar strength

The width/height ratio determines the strength of a pillar. For Estonian oil shale mines the factor of the pillar form is presented as follows (7):

\[ K_3 = \frac{1}{0.7 + 0.3 \frac{x - q}{h}} \]  \hspace{1cm} (6)

where \( x \) – pillar width, m; \( h \) – pillar height; \( q \) – factor of the pillar side destruction, when blasting works are used (\( q = 0.6 \) m), \( q = 0 \) mining works without blasting.

In Estonian oil shale mines the height of a pillar is less than width. Consequently, the factor of the pillar form \( K_3 < 1 \).

4.4. Pillar strength dependence on excavation depth

A commercial oil shale bed (pillar) consists of oil shale and limestone seams. The characteristics of certain oil shale and limestone seams are quite different. The strength of the rock increases in the southward direction. The data on 258 boreholes of Estonian oil shale deposit were analyzed and compressive strength of pillars calculated. The rate of rock strength increase is presented by the following empirical formula:

\[ K_4 = \frac{1}{0.0068H + 0.72} \]  \hspace{1cm} (7)

Rock strength rate \( K_4 \leq 1 \) (from 40-90 m). For the depth of excavation \( H \leq 40 \) m \( K_4 = 1 \).

4.5. The influence of tectonic jointing on the strength of rocks

Tectonic jointing determines the stability of the roof and pillars. Classification is based on the joint spacing (7). For Estonian oil shale mines, the ratio of the stability is presented in Table 1.
Table 1. Classification of jointing, the coefficient (7) and ratio of the stability

<table>
<thead>
<tr>
<th>Type of the roof</th>
<th>Stability of the roof</th>
<th>Joint spacing, m</th>
<th>Coefficient of the stability</th>
<th>Ratio of the stability, K_5</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>High</td>
<td>&gt;20</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>2</td>
<td>Medium</td>
<td>10-20</td>
<td>0.85</td>
<td>1.18</td>
</tr>
<tr>
<td>3</td>
<td>Low</td>
<td>5-10</td>
<td>0.70</td>
<td>1.43</td>
</tr>
<tr>
<td>4</td>
<td>Unstable</td>
<td>3-5</td>
<td>0.55</td>
<td>1.82</td>
</tr>
</tbody>
</table>

4.6. Load distribution between the pillars of different cross-section area (8)
The load on a pillar depends on the stiffness of the roof and pillar. The roof in Estonian oil shale mines is stiff enough and in this case a bigger pillar receives a greater load. The failure begins from bigger pillars. Consequently, the distribution of the cross-section area of the pillars determines the load on the pillar. Normal distribution control of the pillar cross-sectional area made in the Ahtme and Estonia mines is presented in Figure 3.

![Figure 3](image)

Figure 3. Normal distribution control of the pillars cross-sectional area (8)
A – normal distribution; B – no normal distribution.

The deviation of the pillars cross-section area from its mean value in Estonia mine is less than in Ahtme. Consequently, pillars sizes differ less and they are stronger, if the normal distribution is not present. This process demands supplementary investigations and calculation method is to be worked out.

5. Conclusions and recommendations
1. The problem of post-technological processes influencing the environment is most topical in a densely populated and intensely farmed district like NE Estonia.
2. The applicability of the conditional thickness method for long-term prediction of mining block stability is demonstrated in theory. The uncertainty in time is less than 10% at the 95% confidence level. This method is of particular interest for practical purposes.
3. The method allows determining the mining block collapse time, location, and area. The surface subsidence parameters can be calculated by conventional calculation schemes.
4. Prediction by conditional thickness is applicable in different geological condition, where the room-and-pillar mining system is used.

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