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Risk assessment of seismic impact on the roof and pillars stability in Estonian underground

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Abstract. The processes of immediate roof exfoliation and pillars collapse is accompanied by significant subsidence of the ground surface. Ground surface subsidence causes soil erosion and flooding, swamp formation, agricultural damage, deforestation, changes in landscape, ground water level decreasing and the formation of unstable cavities. For the last four years a new blasting technology with great entry advance rates (EAR) has been introduced in an experimental mining block. By improved blasting technique the EAR reached 4 m; it is twice greater in comparison with usual technology, but emulsion explosive volume is twice higher and explosion occurs for 4.5 seconds (about 15 times longer than with the old technology). As a result of such greater advance rates, unsupported room lengths up to 5.5 m with decreasing stability of the immediate roof (IR) can be expected. In this paper the analysis of the IR stability using the deformation criteria for a new room-and-pillar mining technology with modern machinery at "Estonia" mine is presented. The analysis of the IR stability is based on the on-site underground testing by using benchmark stations and convergence measurements. The target of this study is to determine the impact of the vibration on the roof and pillars stability using the risk assessment method. Risk analysis on the basis of available earthquake data is also carried out.

Key words: deformation, room-and-pillar mining, immediate roof, stability, risk analysis, particle peak velocity.

1. INTRODUCTION

Underground oil shale mining in Estonia is carried out by room-and-pillar method with blasting. This method is cheap, highly productive, easy to mechanize and relatively simple to design [1]. The main problems of the current technology are the following: the great volume of blasting operations, low mobility and concentration of loading works due to the small entry advance rates, about 1.5–1.7 m per blasting [1]. One of the ways to improve the quality of mining operations is updating of the drilling-and-blasting method.

New blasting technology with great entry advance rates has been used at the “Estonia” mine for the last four years. With improved blasting technology the EAR reached 4 m, that is twice greater compared with ordinary technology. The average productivity of such technology is about 3000 m^3 of mined rock per day. Blasting with 79.5 kg charge per one face has higher entry advance rate and lower specific charge. Because of the high quantity of the explosive, the problems of the rooms and pillars stability, caused by blasting waves, arise.

New technology in two mining blocks, 3103 and 3104, at the “Estonia” mine was tested for the last period [2]. Geological conditions were quite different. Typical excavation height is about 2.8 m, but in the case of weak IR conditions, like in our blocks, it can be up to 3.8–3.9 m. Roof support is achieved by using the Steeledale SCS roof bail type anchor bolts. In this case the expander plug (anchor lock) must be fixed in the harder limestone layer G/H. It improves roof control significantly, reducing bolt-to-face distances and exposure of the unsupported roof. The width of the room is determined by the stability of the immediate roof. As a result of such greater EAR, situations with unsupported rooms up to 7 × 5.5 m with decreasing stability of the immediate roof can be expected. The analysis of the IR stability is based on in-site underground testing by leaving benchmark stations (BMS) and convergence measurements (Fig. 1).

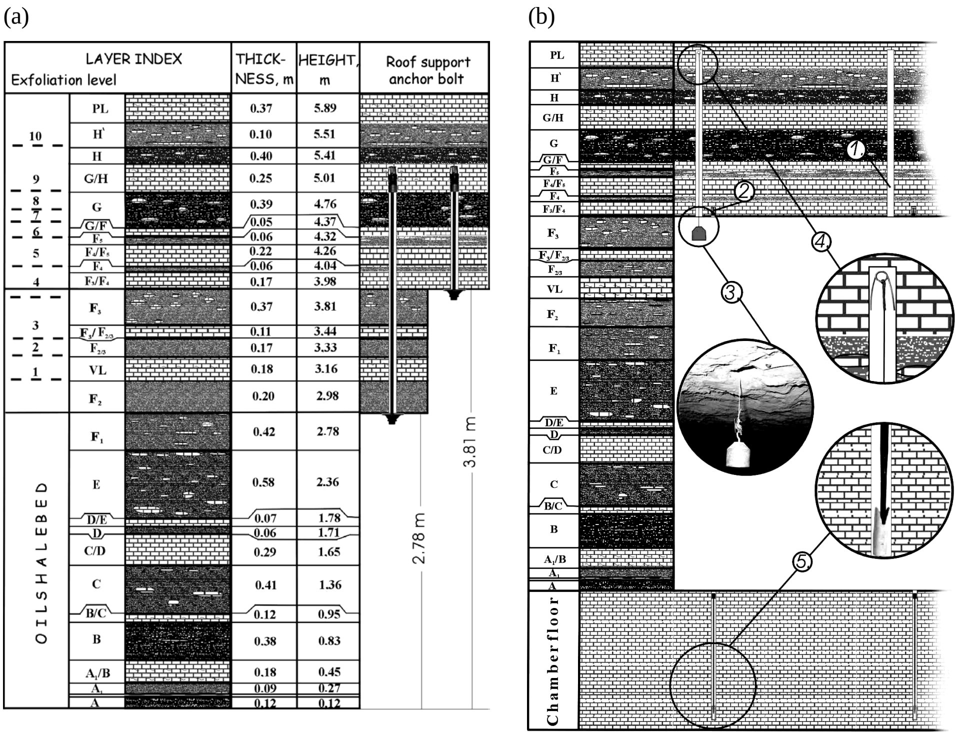

Fig. 1. Structural cross-section with determined IR exfoliation levels (a) and scheme of benchmark stations in the roof/floor (b): 1 – borehole for stratascope; 2 – benchmark station on the roof; 3 – bob for rope-benchmark station; 4 – rope-benchmark station; 5 – benchmark station in the floor.

2. PREDICTION OF STABILITY USING ROOF-TO-FLOOR CONVERGENCE DATA

Laminated roof deformation on the basis of the plate hypothesis, using experimental data of the Institute of Mining Surveying (VNIMI) in St. Petersburg and Estonian department of the A. A. Skotchinsky Institute of Mining Engineering (IGD, Moscow) is presented in Fig. 2 [3,4].

In the general case it is possible to distinguish four stages of this process for Estonian oil shale deposit. *Instant deformations* ε up to 10 mm appear after the first blasting during a short time interval. Then in time (duration depends on geological conditions) there are two processes: an increase of *elastic deformations* due to rheological processes, blasting work and entry advance, and also increase of *creep deformations* up to the cracks formation moment at $t = t_1$, when $\varepsilon = 20–30$ mm. Then instead of a plate the arch on three hinges is formed completely. The time period from t_1 to t_2 is a *transient creep* period due to the partial crushing of average and left/right hinges of an arch, till the moment of the crushing termination, when $\varepsilon = 60$ mm. During the period from t_2 to t_3 there is a *steady-state creep* (SSC) in hinges up to their full crush at t_3, when $\varepsilon = 110$ mm and full loss of the roof bearing capacity (full destruction up to depth 2–3.5 m) happens. Duration of the time period from t_0 to t_3 depends on many *geological* (loading, capacity, cracks, etc.) and *technological* (critical roof area, character of the explosion, advance rate, supporting etc.) factors that present difficulties for finding the dependence $\varepsilon = f(t)$.

During on-site testing 16 pairs of BMS were installed and 19 holes were viewed by the stratascope in two mining blocks (3103 and 3104) with different geological conditions (with weak and average stable IR) [5]. The results of IR

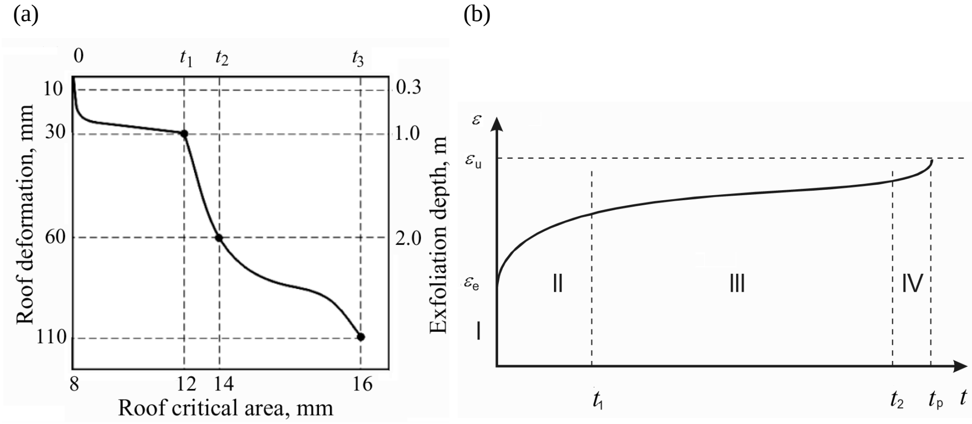

Fig. 2. Roof-to-floor convergence curve by VNIMI and IGD data (a) and typical curve for the long-term stability analysis (b) [3]: t – time; $t_p = t_3$ – time at failure; ε – deformation; ε_u – ultimate deformation at failure; ε_e – elastic deformation; I – elastic deformation ε_e; II – transient creep $\dot{\varepsilon} < 0$ ($\dot{\varepsilon}$ – deformation rate); III – steady-state creep ($\dot{\varepsilon}$ = const); IV – transient creep ($\dot{\varepsilon} > 0$).

(at the centre of the room) and pillars ($S = 45–50\ m^2$) average deformation are presented in Fig. 3. For our conditions critical dimensions (L) of the rooms were about 11–12 m.

According to VNIMI and IGD data the roof failure happens (depth of failure is about 2.0–3.5 m) when deformation is $f_{max} = 6.3L = 8.84A + 5.3$ mm, where A is the room width. Under our conditions, $f_{max} = 8.84 \times 7.0 + 5.3 = 67$ mm. Experimental data are much closer to the data of VNIMI and IGD. It means that the improved technology influences on immediate roof stability estimated by the deformation criterion is not greater than with old technology. Analysis of immediate roof failure cases during the experiment shows that the depth of failure is about 8–10 cm when $\varepsilon = 0.4 f_{max}$ is possible. Then after IR unsupporting the failure on this depth can be expected with great probability.

By the measuring exfoliation level or depth and deflection rate (DR) of IR we can estimate the effectiveness of anchor bolting and the supporting pattern. Deflection rate of the system “anchor–roof” by the anchor torque measurements was on average 1.3 mm/t, where loads on used anchors (N) was determined by the empirical formula $N = 0.2722\,M$ (M is anchor torque). In this case DR is a parameter of IR deformation after the vertical load on anchor increasing by one ton [6,7].

Measured IR deformation (D_{IR}) by BMS, installed in the rooms, were evaluated by Severity scale criteria. Evaluation of the total amount of inspected rooms was made using the Boundaries scale.

Severity scale, S.

5 – Severe-catastrophic (very harmful or potentially fatal; great effort to correct and recover, $D_{IR} \geq 110$ mm)
4 – Serious-harmful, but not potentially fatal, difficult to correct but recoverable ($D_{IR} = 61–110$ mm, t_3)
3 – Moderate – somewhat harmful, correctable ($D_{IR} = 31–60$ mm, t_2)
2 – Mild – little potential for harm, easily correctable ($D_{IR} = 11–30$ mm, t_1)
1 – Harmless – no potential for harm, correctable ($D_{IR} = 0–10$ mm, t_0)

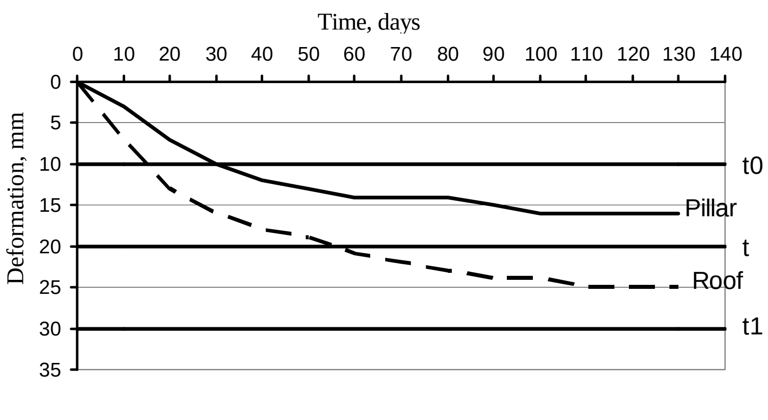

Fig. 3. Roof-to-floor convergence curves in mining blocks 3104 and 3105.

Boundaries scale, B.

5 – Local, impact migrates on ground surface
4 – Not confined, impact migrates outside critical area (25–30 rooms)
3 – Weakly confined, impact migrates off-site one row of the rooms
2 – Confined, impact migrates off-site four rooms, but is contained in small area
1 – Isolated, impact is considered in one room

As control criterion we used SB: 1–10 – controllable (process under control); 11–15 – influenceable (process controlled by changing the technology; 16–20 – process is not controlled. For our experimental mining blocks process was always under control.

3. RISK ANALYSIS OF THE EARTHQUAKE INFLUENCE ON THE ROCK MASSIVE

Three earthquakes were registered in the Baltic region during the short period 21.01.2005–04.02.2005. Absolute deformations near pillars after earthquake had a jumping character. Data on two of them is given in Table 1.

Knowing velocity of massive fluctuations (acceleration) at which occurs pressure causing infringements or collapse in mining developments, it is possible to judge comparative stability under seismic loadings and seismo-explosive shock waves. On the basis of such data it is possible to estimate admissible and critical peak particle velocities at which mining development stability is lost.

According to [8] admissible peak particle velocity for supporting by the timbering, strengthened by anchors, is 0.9 m/s and critical velocity 1.2 m/s. According to Estonian standards the same numbers are valid for railway tunnels and subway overpasses.

In USSR standards for underground constructions with service life t up to 4–10 years the critical peak particle velocity is no more than 0.12 m/s, and for $t \leq 3$ years no more than 0.48 m/s [9]. In Estonia, the maximum resolved peak particle velocity for open-cast boards makes 0.48 m/s.

Knowing the basic physical-mechanical properties of the rock, such as the velocity of longitudinal waves V_p, ultimate extension strength σ_r, Young's

Table 1. Data of earthquakes on 27.01. and 29.01.2005

Magnitude	mb 4.3	mb 3.8
Region	BALTIC STATES-BELARUS-NW RUSSIA	BALTIC STATES-BELARUS-NW RUSSIA
Date, time	27.01.2005 at 14:07:26.7 UTC	29.01.2005 at 13:17:48.0 UTC
Location	57.23 N; 25.15 E	58.96 N; 22.70 E
Depth, km	25	25
Distances to reference points	73 km NE Riga; 12 km SW Cēsis	128 km W Tallinn; 5 km SW Kärdla

modulus E, it is possible to calculate the critical peak particle velocity V_d from the formula [10]

$$V_d = V_p \, \sigma_r / E. \tag{1}$$

According to the data from the Institute of Oil Shale during the experiment at "Tammiku" mine, the velocity of longitudinal seismic waves was 1700 m/s [11]. The velocity of longitudinal seismic waves, measured by the Japanese company KOMATSU in 2002 at "Narva" pit was from 1039 to 2000 m/s [12]. According to the report of the Institute of Oil Shale, the Young modulus for layer C in Estonia (one of the weakest) is $E \cong 7100$ MPa and σ_r varies from 2.5 to 3.5 MPa. Thus for $\sigma_r = 2.5$ MPa Eq. (1) gives $V_d = 0.37$ m/s and for $\sigma_r = 3.5$ MPa we have $V_d = 0.84$ m/s.

Hence, critical velocity of massive displacement for the industrial layer in Estonian oil shale deposits makes 0.4–0.8 m/s.

4. RICHTER MAGNITUDE AND TNT EQUIVALENT

The Richter magnitudes are based on a logarithmic scale (base 10). According to the data of Michigan Technological University [13], earthquake of magnitude 8 releases as much energy as detonating 6 million tons of TNT. This statement is based on the empirical formula

$$\log E = 1.5M, \tag{2}$$

where M is Richter magnitude and E is energy.

The American Institute of Makers of Explosives (IME) [14] has suggested the following formula for the calculation of the TNT equivalent T_{NT}:

$$T_{\mathrm{NT}} = \frac{MQ}{4.186 \times 1090}, \tag{3}$$

where Q is the blasting energy.

The blasting energy of Nobelite 2000 is 2600 kJ/kg, and that of TNT 4.186×1090 kJ/kg. Thus to one kg of TNT corresponds about 1.6 kg of Nobelite 2000.

5. DETERMINATION OF THE PEAK PARTICLE VELOCITY

It is obvious that peak particle velocity V_{pp} depends directly on such parameters as distance from the explosion, quantities of blasted explosives on delay unit and on the basic physical and mechanical properties of the rock. The value of V_{pp} is calculated as

$$V_{pp} = A\left(\frac{D}{\sqrt{W}}\right)^{-n}, \text{ mm/s,} \tag{4}$$

where A is degree of damping of V_{pp}, n is an exponent depending on the type of the explosive, W is quantity of the explosive and D is distance to the location of the explosion.

According to [15] blasting factors in Estonian underground conditions (ammonite 6ZV) have the following values: $A = 1748$, $n = 1.25$.

6. RISK ESTIMATION OF THE UNDERGROUND CONSTRUCTION STABILITY

About 12 earthquakes with magnitudes $2.38 \le 2.7 \le 3.02$ $(p = 0.95)$ and from 1 to 2 earthquakes with magnitude 3.5–3.9 occur on the territory of Estonia every 100 years. Last earthquakes on the territory of Estonia were recorded in the area of the islands Hiiumaa and Osmussaare (their distance from the "Estonia" mine is about 250 km). We shall determine earthquake magnitude in the area of these islands, capable to influence the stability of underground constructions:

$$V_{pp} = 1748\left(\frac{250\times10^3}{\sqrt{9\times10^8}}\right)^{-1.25} = V_d = 0.12 \text{ m/s.} \tag{5}$$

The value $W = 9\times10^8$ kg corresponds to magnitude about 7.5 [15]. It is necessary to note the fact that the given formula is rather conservative at distances more than 30 m. Application of Eq. (15) for greater distances can lead to probable deviation for more than 5%. For the more exact estimation, it is necessary to consider such basic earthquake characteristics as depth of the epicentre, amplitude, frequency, structure of the overburden and mechanical parameters of the rocks.

From the calculation results we can conclude that probability of the influence of earthquakes on the underground constructions in Estonian oil shale mines is insignificant. But if earthquake magnitude makes 4 or more and the epicentre occurs directly under the underground construction it may influence dangerously the mining block stability. At earthquake magnitude 6, safety distances for the mining block exceed 27 km, at magnitude 7 about 150 km and at magnitude 8 about 850 km.

7. CONCLUSIONS

1. Immediate roof stability estimated by using the deformation criterion is not greater than that obtained with the old method.
2. Analysis of immediate roof failure cases during the experiment shows that the depth of failure about 8–10 cm when $\varepsilon = 0.4 f_{\max}$ is possible.

3. Calculations of the peak particle velocity show that, influence of the earthquake on the underground constructions can be excluded. If earthquake magnitude is 4 or more and epicentre is located directly below the underground construction, it may dangerously influence the mining block stability.
4. Investigation shows that by using the new blasting technology the influence of blasting works on the stability of mining blocks is not greater than by using the old technology.

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Seismiliste lainete mõju riski hindamine tervikute ja lagede püsivusele Eesti kaevandustes

Sergei Sabanov, Jüri-Rivaldo Pastarus, Oleg Nikitin ja Erik Väli

Viimase nelja aasta jooksul on Eesti põlevkivikaevandustes evitatud uus lõhketööde tehnoloogia. Ee edasinihe 4 m traditsioonilise 2 m asemel tagab mäetööde suurema efektiivsuse. Uue tehnoloogia kasutamisel on lõhketsükli aeg 15 korda pikem ja lõhkeaine hulk ning toestamata lae pindala kaks korda suurem, võrreldes traditsioonilise tehnoloogiaga. Seoses sellega kerkib päevakorda tervikute ja lagede püsivuse probleem, millest sõltub allmaatööde efektiivsus ning maapinna püsivus. Töö eesmärgiks on määrata seismiliste lainete mõju lagede ja tervikute püsivusele, kasutades riski hindamise metoodikat. Artiklis on esitatud lõhketööde ja maavärinate võrdlev analüüs. Uuringud on näidanud, et lõhketööde mõju lagede ja tervikute püsivusele (magnituudil ~7,5) on suurem kui maavärinatel, mille magnituudi maksimaalne väärtus viimase 100 aasta jooksul on olnud ligikaudu 4. Riskianalüüsist tuleneb, et uue lõhketööde tehnoloogia kasutamine ei mõjuta oluliselt lagede ja tervikute deformatsioone, seega ka maapinna püsivust.