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SURFACE MINING TECHNOLOGY IN THE ZONES OF TECTONIC DISTURBANCES, ESTONIAN OIL SHALE DEPOSIT

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Abstract. *The 150–300 m thick Ediacaran-Devonian sedimentary cover of Estonia, which contains the commercial oil shale deposit, is divided into blocks by linear fracture and tectonic disturbance zones. Along these zones the bedrock is modified, its composition and strength parameters are changed. Often there are restrictions on the use of new surface-mining areas as local people oppose excavation activities near their homes. Indirect methods were used for determination of the uniaxial compressive strength of rock. A wide variety of rock structures were considered and different excavation methods studied. Feasible mining technologies near the zones of tectonic disturbances have been proposed.*

Keywords: *excavation methods, open cast, digging, ripping, blasting, hydraulic breaking, geological conditions, uniaxial compressive strength, productivity, zone of tectonic disturbances.*

1. Introduction

Estonia is located in the NW marginal zone of the East-European Platform where the SE slope of 2.1–1.6 Ga old Paleoproterozoic strongly folded crystalline metamorphic and intrusive rocks of the Fennoscandian Shield is covered by the 635–358 Ma old Ediacaran and Paleozoic sedimentary cover [1]. The eroded upper surface of the Precambrian basement is slightly

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inclined to south, about 2.2–2.5 m per km. On the shoreline of the Gulf of Finland basement lies at about 150 m and on the northern shore of Lake Peipsi at 270–280 m below sea level [2].

The Estonian oil shale deposit, which was formed about 458–456 Ma ago, constitutes a 135 km elongated lens-shaped body of EW direction in the lowermost part of the Kukruse Stage of the Upper Ordovician limestone bedrock in NE Estonia [1]. In its eastern part near the Estonian–Russian borderline on the Narva River the width of the deposit is about 45 km, which gradually narrows down to 10–15 km in the westernmost part [3, 4]. The economic bed is cropping out 5–10 km to the south of the shoreline of the Gulf of Finland, in the 1.5–2 km zone, and dips gently to the south, about 2.9 m per km. The mining depth varies from 5 to 150 m. Surface mining works are carried out at a depth down to 30 m, but this is complicated due to difficulties in removing the overburden rocks, as well as in terms of economic considerations.

With reference to fracture, presence of disturbance zones, tectonic jointing, occurrence of karsts, as well as hydrothermal mineralization, the Estonian oil shale deposit is of complex structure. The overburden rocks are represented by the limestone sequence of different strength and geological parameters. Sometimes there are zones of tectonic disturbances which complicate surface mining works.

The main aim of the present work is to determine geological and mechanical (strength) parameters of overburden rocks in the tectonic disturbance zones of the Estonian oil shale deposit, and propose feasible mining technologies. By surface mining different excavation methods may be used such as digging, ripping, hydraulic breaking and blasting. When employing hydraulic breaking, mineral resource quality, mining conditions and restrictions have to be taken into account [5–8]. Considering these factors general recommendations for mining in the deposit may be given [9, 10]. The application of stripping and separation technologies will deteriorate soil properties [11, 12]. The thickness and properties of the overburden are also important when choosing a mining technology [13, 14]. The output and properties of the mineable mineral depend on the chosen technology as well [15]. The choice of a particular mining technology and use of a mining field will depend on previous experience and valid legislation [16]. As shown in this paper, in preparing the pertinent legislation previous experience in the sphere, but mainly related restrictions are taken into account [15, 17].

In different mining areas there may be restrictions prohibiting the use of an explosive or hydraulic breaker [18–20]. Drilling and blasting are accompanied by extensive ground vibration, which affects nearby inhabitation, cracks the ground and structures, and produces a lot of noise and dust. In this case ripping is more suited. Ripping and hydraulic breaking are continuous operations, which reduces the time the machines stand idle. The shifting of machines is also avoided. These techniques provide higher safety and slope stability as well. Generally, ripping is the most cost-effective method of mining.

The total thickness of the Kukruse Stage in the main oil-shale mining region of Estonia is about 14 m [21]. The commercial bed consists of seven oil shale seams with 6–59 cm each, their total thickness being 2.06 m. Oil shale seams are alternated by five limestone intercalations, each of them 6–30 cm thick, with a total thickness of 72 cm [22]. The thickness of the entire commercial bed is about 2.80 m. It means that the overburden is mostly composed of the upper part of Kukruse (11 m) and Haljala stages, the thickness in NE Estonia being 14–20 m. The lower part of the Kukruse Stage is represented by oil shale seams with carbonate nodules alternating with pure limestone and kerogenous limestone with kukersite nodules. The central part of the stage contains less kerogenous material and more pure limestone layers with a thickness of 10–40 cm, and kerogenous limestone with kukersite nodules. The upper part of the stage is composed of oil shale with limestone nodules and kerogenous limestones with pure limestone intercalations. The lower part of the Haljala Stage comprises bedded hard limestone, argillaceous limestone with intercalations of marls and some thin K-bentonites horizons, its upper part consisting of argillaceous bedded to nodular limestone with intercalations in the middle part [21].

The bedrock of the overburden is not used in building, so its physico-mechanical properties are not studied in this paper. The compressive strength of limestone and dolomitized limestone may reach 60–100 MPa, and that of dolostone even higher [23]. Dolomitization and recrystallization are of wide occurrence in the carbonaceous bedrock in the eastern part of the Estonian oil shale deposit along tectonic disturbance zones, which enhances the bedrock's strength and other physico-mechanical properties [24, 25].

A wide variety of rock structures were considered. Rock strength parameters were determined by indirect test methods, using classification hammer and point load apparatus. Uniaxial compressive strength was calculated by empirical relationship. Assessment of different excavation methods is based on rock characteristics, which is far more accurate.

2. Strength parameters of rock

The procedure for measuring uniaxial compressive strength (UCS) has been standardized by the International Society for Rock Mechanics (ISRM) [26]. However, this method is time consuming and expensive. Indirect tests such as point load index (Point Load Test) and rebound number (Rock Classification Hammer) are used to predict UCS. These tests are the most widely used indirect classification tests for rocks [27–31]. They are easier to carry out because necessitate less or no sample preparation and the testing equipment is less sophisticated too. Also, they can easily be employed in the field.

2.1. Rock classification hammer

The rock classification hammer (45-D0561) is a non-destructive, portable test device [32]. It consists of a plunger and a spring-loaded hammer. When triggered, the hammer strikes the free end of the plunger that is in contact with rock, which in turn causes the plunger to rebound. The extent of the rebound is indicated on the linear scale attached to the device.

The rebound reading will be affected by the orientation of the hammer. To compensate for these differences, correlation factors are used corresponding to the diverse impact positions or angles. The area and the rock material at a depth greater than 6 cm shall be free from cracks, or any localized discontinuity of the rock mass. At least 24 individual readings are necessary to obtain a representative mean of a given test.

The uniaxial compressive strength (UCS) depends on the following factors:

$$UCS = f(\alpha, \gamma, I_p), \tag{1}$$

where UCS is the uniaxial compressive strength, MPa, α is the impact position or angle, γ is the weight density, kN/m^3, and I_p is the rebound number.

Consequently, the corrected rebound number and weight density of rock can be used to estimate rock strength parameters. The procedure for UCS determination can be obtained graphically or by empirical relationships.

2.2. Point load test

A digital rock strength index apparatus 45-D0550/E is used to obtain quick information concerning rock strength indexes [33]. The International Society for Rock Mechanics [26] has established basic procedures for testing point load strength and calculating the point load strength index.

The test consists in compressing to failure a core or irregular block of rock sample by applying the point load by a couple of steel conical points of standard size. It is possible to operate with rock samples of different diameter (between 15 and 85 mm) and shape. The test is repeated with at least 10 core or lump samples coming from the same original type of rock. The point load test (PLT) allows the determination of the uncorrected point load strength index I_s. It must be corrected to the standard equivalent diameter D_E of 50 mm $I_{S(50)}$ [33]. The procedure for size correction can be obtained graphically or mathematically as outlined by the ISRM procedures. Load strength index can be used to estimate other rock strength parameters.

In order to estimate uniaxial compressive strength (UCS), index-to-strength conversion factors are used. These factors have been proposed by various researchers and are dependent upon rock type. All specialists agree that UCS increases with increasing point load strength index [28]. It is noteworthy that different authors offer different values for conversation factors. Consequently, conversation factors are not universal and depend on type of rocks. The conversation factor for sedimentary rocks is in the range between 16 and 24 [28–31, 34, 35]. The following linear regression model is used to correlate UCS and $I_{S(50)}$:

$$UCS = (16 - 24)\, I_{s(50)}, \qquad (2)$$

where UCS is the uniaxial compressive strength, MPa, and $I_{s(50)}$ is the standardized load strength index.

2.3. Results

Rock classification hammer and point load tests were carried out under in situ conditions. The classification hammer test was made using irregular blocks of rock sample. These were extracted from the limestone massive. The point load test was performed directly on the limestone massive. The results obtained by both tests may be considered representative and are presented in Table 1.

Table 1. Uniaxial compressive strength of limestone

Parameters	Rock classification hammer		Point load test	
	Tectonic disturbance zones	Normal conditions (no tectonic disturbance zones)	Tectonic disturbance zones	Normal conditions (no tectonic disturbance zones)
Number of measurements	210	60	36	11
Uniaxial compressive strength, MPa	45	25	45	34
Variation factor, %	10–18	11–25	21–43	31–57

Analysis showed that the uniaxial compressive strength of overburden rocks is greater in tectonic disturbance zones than in normal conditions, i.e. in zones with no tectonic disturbances. It is important to note that the overburden rocks contain layers of lower strength. The reliability of the results obtained by the rock classification hammer test is guaranteed by the sufficient number of measurements and is also confirmed by the low variation factor. The point load test gives a high variation factor, which is due to the smaller number of measurements.

3. Choice of an excavation method

Different excavation methods, including digging, ripping, hydraulic breaking and blasting, are used in Estonian open casts in the zones of tectonic disturbances. The choice of the most feasible excavation technology is based on different rock characteristics [18, 20]. Figure 1 shows a rough chart of various excavation methods considering several rock types.

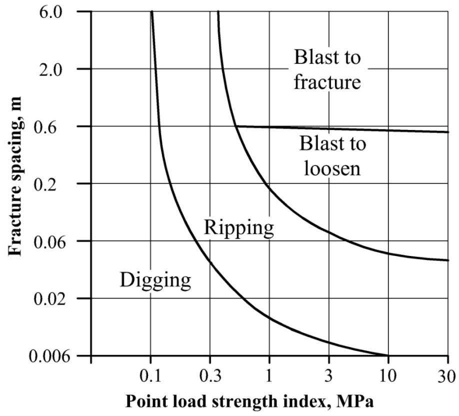

Fig. 1. Rock quality classification in relation to excavation method [18, 20].

It is important to note that blasting and hydraulic breaking are applicable to all types of rock. Ripping is a viable alternative to blasting and hydraulic breaking. By ripping, the ripper shank is pulled through the rock to fragment the material, which can then be loaded by different mechanisms. Ripping is an inexpensive method of breaking soft rock masses. Rippability can be determined using two methods [18, 20]:

1. direct method which includes a direct field trial at the site with available equipment;
2. indirect method which is based on considering various material properties and seismic velocity of the strata.

The most common indirect method is based on seismic velocity, but this may vary as much as 1 km/s in case of identical materials [36]. Investigation has shown that assessment of rippability based on rock characteristics is far more accurate. Table 2 provides excavation method characteristics for a wide variety of materials [20].

In the mining industry excavation and demolition work is carried out using a hydraulic hammer. In spite of the availability of more modern hydraulic hammers, still, noise and vibration make their use in mining operations complicated. Recently a ripper was developed to perform excavation and demolition in less time, at lower cost and with minimum noise and vibration. Comparison of the productivity of the ripper and hydraulic breaker is presented in Figure 2 [18, 20, 36].

The investigation has shown that the productivity of the hydraulic breaker does not depend much on rock characteristics. Analysis also demonstrated that the productivity of the ripper, which depends a great deal on the uniaxial compressive strength of rock, is two to five times higher than that of the hydraulic breaker.

Investigations under in situ conditions show that in the zones of tectonic disturbances of the Estonian oil shale deposit the USC of limestone layers is up to 45 MPa at a depth of 20–35 cm. In this case limestone layers are classified as extremely or very hard to rip (see Table 2). Mining is possible only by using blasting, or hydraulic breakers.

Table 2. Excavation method characteristics in relation to rock strength and joint spacing

Rock hardness and strength			Joint spacing		
Rock hardness description	UCS, MPa	Excavation method characteristics	Joint spacing description	Joint spacing, mm	Excavation method characteristics
Very soft rock	1.7–3.0	Easy ripping	Very close	< 50	Easy ripping
Soft rock	1.0–10.0	Hard ripping	Close	50–300	Hard ripping
Hard rock	10.0–20.0	Very hard ripping	Moderately close	300–1000	Very hard ripping
Very hard rock	20.0–70.0	Extremely hard ripping or blasting	Wide	1000–3000	Extremely hard ripping or blasting
Extremely hard rock	> 70.0	Blasting	Very wide	> 3000	Blasting

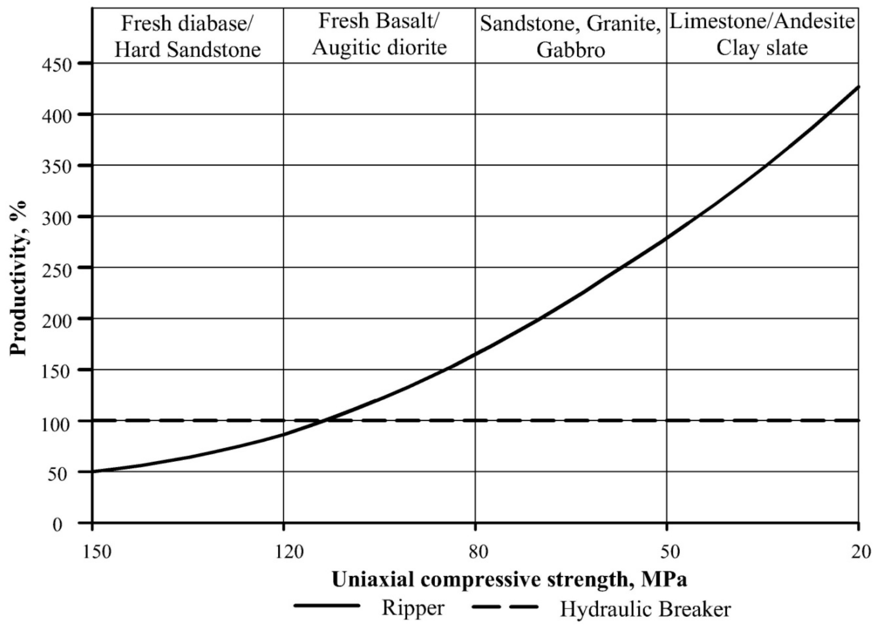

Fig. 2. Productivity of hydraulic breaker versus ripper (thickness of layer < 50 cm).

4. Conclusions and recommendations

The choice of surface mining technology in the zones of tectonic disturbances is complicated, depending on local geological conditions and properties of rocks.

The Ediacaran-Devonian sedimentary cover of Estonia, which contains the commercial oil shale deposit, is divided into blocks by linear fracture and tectonic disturbance zones. Along these zones the bedrock is modified, its composition and strength parameters are changed. Dolomitization and recrystallization of the carbonaceous bedrock enhance its strength and physico-mechanical properties. The compressive strength of limestone layers with a thickness of 10–40 cm is up to 100 MPa, being even higher for dolostone.

Determination of the strength parameters of rock under in situ conditions was carried out using indirect investigation methods. Uniaxial compressive strength was obtained by empirical relationship. The investigation showed that the uniaxial compressive strength of rock in the zones of tectonic disturbances is 45 MPa, which is higher than in normal conditions. In the overburden rocks there are some layers of lower strength.

A wide variety of rock structures were considered and different excavation methods studied, including digging, ripping, hydraulic breaking and blasting. Analysis was based on different rock characteristics and geological features. Feasible mining technologies to be applied to oil shale mining in tectonic disturbance zones and considering restrictions prohibiting the use of an explosive or hydraulic breaker have been proposed.

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