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PHYSICAL AND MECHANICAL PARAMETERS OF BOREHOLE HYDRAULIC MINING OF NONG'AN OIL SHALE

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Abstract. *The experiments on physics and mechanics of borehole hydraulic mining were designed to determine mechanical characteristics of mined oil shale. Oil shale of Nong'an deposit belongs to slightly weathered and relatively complete rocks. Oil shale beds are characterized by a very definite discontinuity in both horizontal bedding orientation and vertical bedding direction. Compressive strength, tensile strength, Poisson's ratio and other data characterizing oil shale beds in different directions in the Nong'an mining site were obtained and compared. The direction of borehole hydraulic mining was determined. The vertical bedding direction to break oil shale was considered to be better, because strength in this direction is low, rock mass integrity poor, and the degree of weathering more pronounced. The diameter of borer nozzle, dynamic pressure, maximum caving capacity and other parameters needed for borehole hydraulic mining were selected.*

Keywords: *oil shale, physical and mechanical properties, parameters of borehole hydraulic mining.*

1. Introduction

Oil shale is an important source of backup energy, and its global reserves are large [1]. Countries are developing research technologies for exploiting oil shale. However, in Nong'an the thickness of oil shale seam is small and oil content is low. The cost of traditional mining is high. The depth of oil shale in Jilin Province is over one hundred meters, which means that opencast mining is excluded [2]. Consequently, the technology of underground *in situ* mining for oil shale is an important means of exploiting oil shale resources in China. *In situ* mining (cracking) of oil shale is a very promising

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technology of exploiting. However, after cracking oil and gas need a transmission channel to reduce delivery resistance. In order to open a channel for oil in an oil shale seam, we used the technology of borehole hydraulic mining. A hydraulic mining drilling system is one of primary means to greatly improve the single-well production at oil shale mining [3].

The value of critical pressure needed for hydraulic breaking of rock increases with compressive strength, tensile strength and hardness of rock, while decreases with an increase in its porosity. So, all the factors affect borehole hydraulic mining. Even more, compressive strength of the rock is comprised of many factors, including mineral composition, grain size, bulk density, porosity, etc [4].

So, the purpose of this experiment was to obtain empirical physical and mechanical parameters of Nong'an oil shale in both horizontal bedding orientation and vertical bedding direction which could serve to determine technological parameters of borehole hydraulic mining for oil shale. The common technical problems of *in situ* mining for oil shale had to be solved as well. For these purposes, oil shale physical and mechanical properties were determined as well as the experiment to study dynamics by the acoustic method was done.

2. Determination of dynamic properties by acoustic method

2.1. Experimental

To follow the standards of pulsating experiments by the acoustic method given in Geotechnical Testing and Monitoring Manual [5], fresh and weathered oil shale and rock samples were measured in both horizontal bedding orientation and vertical bedding direction. Schematic diagram of experiments is shown in Fig. 1 and Fig. 2.

The values of longitudinal wave and shear wave velocities of fresh and weathered oil shale and rock samples, in both horizontal bedding orientation and vertical bedding direction, are given in Table 1. Values in the table are averages of 3–5 tests.

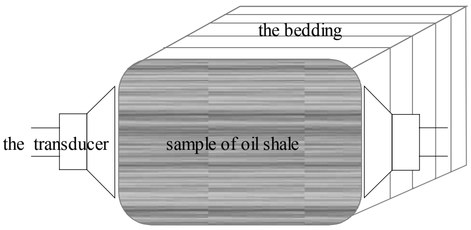


Fig. 1. Test in the horizontal bedding orientation.

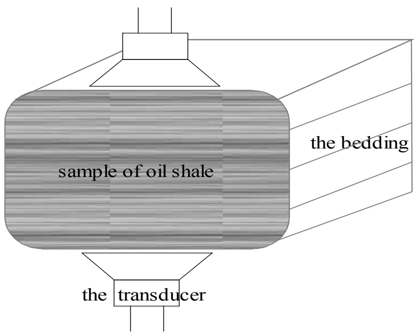


Fig. 2. Test in the vertical bedding direction.

Table 1. Experimental data of the acoustic method

Sample	Test direction	Contact spacing, mm	Velocity of longitudinal wave, m/s	Velocity of shear wave, m/s
Fresh sample of oil shale	horizontal bedding	195	2550	1229
	vertical bedding	60	1629	852
Weathered sample of oil shale	horizontal bedding	16	1561	821
	vertical bedding	7	500	276
Fresh sample of ore	horizontal bedding	675	2894	1580
	vertical bedding	125	1462	812

2.2. The analysis of acoustic method results

Acoustic measurements were carried out to determine the velocities of the longitudinal and shear waves in horizontal bedding and vertical bedding [6]. The dynamic moduli of elasticity (DEM) can be calculated by the DEM formula after measuring the velocities of the longitudinal and shear waves. The DEM formula is:

$$E_d = \rho \times V_p^2 \times (1+\mu_d)(1-2\mu_d)/(1-\mu_d), \quad (1)$$

$$\mu_d = (V_p^2-2V_s^2)/2(V_p^2-V_s^2), \quad (2)$$

where: E_d is DEM value, ρ – density of oil shale, V_p – velocity of longitudinal wave, V_s – velocity of shear wave, μ_d – dynamic Poisson's ratio.

The weathering coefficient can be calculated by the following formula:

$$K_f = (V_{pf} - V_{pw})/V_{pf}, \quad (3)$$

where: K_f is weathering coefficient, V_{pf} – velocity of longitudinal wave in fresh rock, V_{pw} – velocity of longitudinal wave in weathered rock.

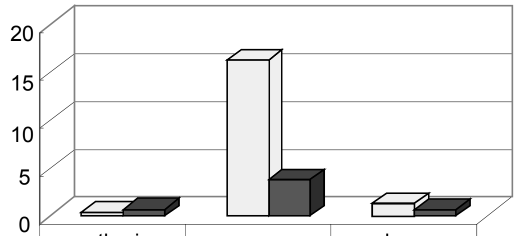
The rock mass integrity coefficient can be calculated by the following formula:

$$K_v = (V_{pm}/V_{pr})^2, \quad (4)$$

where: K_v is rock mass integrity coefficient, V_{pm} – velocity of rock elastic wave, V_{pr} – velocity of elastic wave in the original location of rock.

The parameters of oil shale physical characteristics including dynamic elastic modulus, weathering coefficient and rock mass integrity coefficient are shown in Fig. 3.

Dynamic moduli of elasticity, weathering coefficient, rock mass integrity and other parameters of Nong'an oil shale in both horizontal bedding orientation and vertical bedding direction were determined and compared. The results build up the foundation for borehole hydraulic mining. Weathering coefficient was in the range of $0.40 < K_f < 0.80$. So, Nong'an oil shale belongs to the slight weathered rocks [4]. The mean coefficient K_v for rock mass integrity was greater than 0.76. So, this oil shale is a relatively complete rock. The parameters characterizing horizontal bedding are greater than the ones of vertical bedding, while the weathering coefficient of vertical bedding is greater than that of horizontal bedding.



	weathering coefficient	DEM, GPa	rock mass integrity
horizontal bedding	0.39	16.2	1.29
vertical bedding	0.69	3.8	0.65

Fig. 3. Mechanical and physical properties measured by acoustic method.

3. Determination of oil shale physical and mechanical properties

3.1. Experimental

Following the standards of uniaxial experiments of rock physics and mechanics [5], standard rock samples were drilled and processed. The uniaxial experiments of determining compressive strength and deformation – shear strength test on weak planes and tensile strength test – were carried out on a fresh oil shale sample (see Figures 4 and 5).

The data on tensile strength, shear strength, and normal stress (averages of 3–5 samples) are given in Tables 2, 3, and 4, respectively.

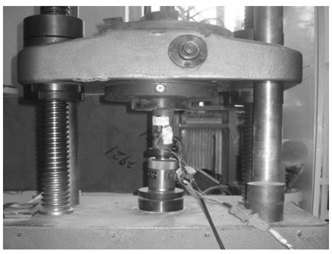


Fig. 4. Uniaxial experiment of compressive strength and deformation.

Fig. 5. Shear strength test on weak planes.

Table 2. Compressive strength of oil shale

Sample		Failure load, kN	Compressive strength, MPa	
			monodrome	mean
Horizontal bedding	No. 1	28.9	16	17
	No. 2	35.3	20	
	No. 3	30	17	
Vertical bedding	No. 1	21.5	12	11
	No. 2	15.8	9	
	No. 3	22.4	12	

Table 3. Tensile strength of oil shale

Sample		Failure load, kN	Tensile strength, MPa	
			monodrome	mean
Horizontal bedding	No. 1	2.56	0.70	0.98
	No. 2	4.30	1.17	
	No. 3	4.0	1.07	
Vertical bedding	No. 1	1.90	0.50	0.46
	No. 2	1.24	0.34	
	No. 3	1.96	0.53	

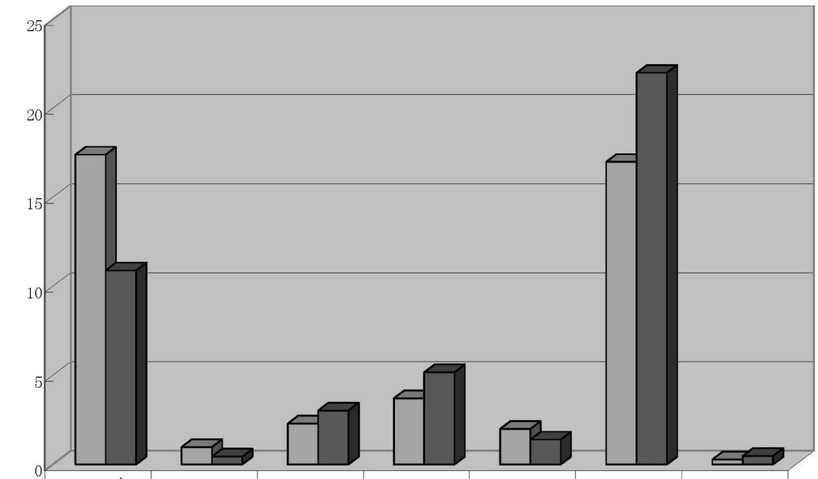
Table 4. Shear strength and normal stress of oil shale

Sample		Vertical load, kN	Normal stress, MPa	Horizontal load, kN	Shear strength, MPa
Vertical bedding	No. 1	4.82	2.64	7.31	4.01
	No. 2	6.70	3.64	9.33	5.07
	No. 3	6.56	3.58	14.36	7.84
	No. 4	4.12	2.26	6.92	3.79
Mean		5.55	3.03	9.48	5.18
Horizontal bedding	No. 1	3.40	1.85	6.66	3.62
	No. 2	5.16	2.81	9.88	5.37
	No. 3	5.40	2.96	4.93	2.70
	No. 4	2.85	1.56	5.86	3.20
Mean		4.20	2.30	6.83	3.72

3. 2. Analysis of experimental results

The data given above together with data on elastic modulus and Poisson's ratio are illustrated in Fig. 6.

Irrespective of the direction, oil shale compressive strength > shear strength >tensile strength. As for tensile strength and compressive strength, the corresponding parameters of horizontal bedding were greater than the ones of vertical bedding, while the corresponding shear strength of vertical bedding was greater than that of horizontal bedding.



	compressive strength, MPa	tensile strength, MPa	normal stress, MPa	shear stress, MPa	cohesion, MPa	internal frictional angle, degree	Poisson's ratio
horizontal bedding	17.41	0.98	2.3	3.72	2	17	0.28
vertical bedding	10.9	0.44	3.03	5.18	1.4	22	0.48

Fig. 6. Properties of Nong'an oil shale.

4. Discussion

The values of compressive strength of oil shale in the vertical bedding direction and horizontal bedding orientation were only 10.9 MPa and 17.4 MPa, both less than the value of compressive strength limiting borehole hydraulic mining. So, it is possible to exploit hydraulic mining of oil shale based on the current technology and equipment. The vertical bedding direction to borehole seems to be preferable. Because the strength of vertical bedding direction was lower, rock mass integrity was poorer and the degree of weathering was largest. Besides, at choosing the mode of hydraulic crushing, tensile fracturing should be chosen, as the tensile strength of Nong'an oil shale was less than other strengths.

The object of oil drilling and mining operations is the rock in the formation. According to the calculation formula of hydraulic pressure of oil engineering work and the analysis of the expediency of using borehole hydraulic mining for exploiting target rocks with different physical and mechanical properties, as well as the analysis of quantitative indicators, the values of coefficient K_o (the value of critical pressure at hydraulic breaking of rock/compressive strength of rock) of hydraulic jet erosion calculated for different rocks are gained, which are 0.1172–0.1228 for mudstone, 0.1249–0.1269 for sandstone, 0.1197–0.1229 for limestone, and 0.1219–0.122 for granite. Our experiment showed that the coefficient K_o of hydraulic jet erosion in oil shale was 0.46 in horizontal bedding orientation and 0.74 in vertical bedding direction. The values meet the requirements of calculation the formula given in reference [8] to determine hydraulic pressure for breaking oil shale in the bottom of the well.

5. Determination of technological parameters for oil shale hydraulic mining

5.1. Technological process of borehole hydraulic mining

According to the range of the impulsive force and mining depth, the seam is divided into zones from No. 1 to n from the bottom upwards. Borehole hydraulic mining is to be conducted from the bottom upwards. First, the borehole hydraulic mining tool (BMT) is placed into the drilling zone No. 1 which is located in the bottom part of the drilling, to do pre-crushing. After that the water (or gas-water mixture) is pressed into the holes through a drilling horse to do hydrofracture. The alternating arrangement of holes for breaking and for water flooding allows a rapid destruction of the bottom of the oil shale bed, leading to the formation of flowing slurry. Large and hard ingredients remain in the drilling zone No. 1. BMT is elevated to the zone No. 2 after finishing mining in the zone No. 1. The process is repeated until all oil shale beds have been mined. The diagram is shown in Fig. 7. In order to

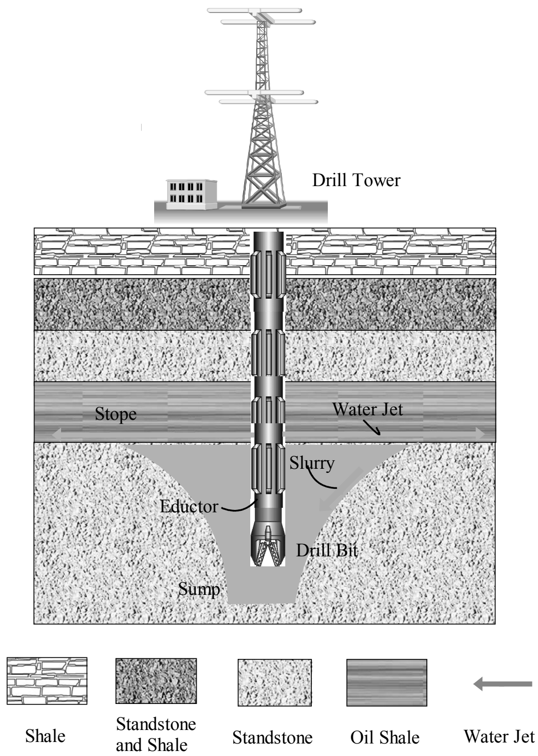


Fig. 7. The diagram of technological process of borehole hydraulic mining for oil shale.

ensure a uniform collapse of the upper ore body, ore slurry extracted from each hole should be consistent [9].

5.2. Main technological parameters of borehole hydraulic mining for Nong'an oil shale

It is necessary to calculate the diameter d_0 [10] of the bore nozzle basing on the formula

$$d_0 = \sqrt{\frac{4Q_0/3600}{u\pi\sqrt{2g \cdot P \cdot 10^2}}}, \tag{5}$$

where: d_0 is the diameter of the nozzle; Q_0 – flow rate used to carry slurry, which depends on the requirements for the velocity of return flow in the central tube (greater than 2 m/s); u – coefficient of useful effect of hydro-elevator, $u = 0.92$; P – pumping pressure, which depends on shear strength and pressure loss along the way as well as on the pressure needed by the jet pump; g – acceleration of gravity.

The main factors that affect solid oil shale at its breakage into lumps which become slurry are physical and mechanical characteristics of oil shale and the pressure of water jet, as well as the available free space for "collapsing" of oil shale into the water. The minimum pressure of mining has to be equal to or greater than the critical pressure causing damage. This dynamic pressure for destruction to be reached could be directly presented by the velocity of high-pressure flow which can be determined by the formula:

$$V_r = \sqrt{\frac{2g\tau_0}{\gamma_0}}, \tag{6}$$

where: V_r is velocity of high-pressure flow representing the dynamic pressure of destruction to be reached; g – acceleration of gravity; τ_0 – shear strength of oil shale; γ_0 – specific weight of water.

The value of shear strength τ_0 measured by mechanical experiments is $\tau_{0\text{horizontal bedding orientation}} = 3.72$ MPa; $\tau_{0\text{vertical bedding direction}} = 5.18$ MPa.

So, the parameters of the velocity of the high-pressure flow are: $V_{r\text{horizontal bedding orientation}} = 86.3$ m/s, $V_{r\text{ vertical bedding direction}} = 101.8$m/s.

Considering that oil shale is hydraulically broken from the vertical bedding direction, the quantity and velocity of the flow in the tool tube can be calculated by the formulas:

$$Q_1 = Q_2 = V_1 \cdot A_1 = V_2 \cdot A_2, \tag{7}$$

$$A_1 = \pi d_1^2/4, \tag{8}$$

$$A_2 = \pi d_0^2/4, \tag{9}$$

where Q_1, V_1, A_1 are quantity and velocity of the flow and cross-sectional area of the pipe, respectively; Q_2, V_2, A_2 – the same parameters in the hydraulic giant; d_l – inside diameter of the tool tube, d_0 – diameter of the nozzle. The value of V_2 is equal to the one of $V_{r\,\text{vertical bedding direction}}$. The diameter of the nozzle was set to 6–10 mm [11]. The outer diameter of the tool tube was 108 mm, and the inside diameter was 73 mm. Lastly, we use the parameters of the hydraulic giant to calculate the related parameters of the pipeline. The calculated data are given in Table 5.

Table 5. Flow parameters in the pipeline

Nozzle diameter, mm	Quantity of flow Q_1, L/min	Velocity of flow V_1, m/s
6	173	0.69
7	197	0.93
8	307	1.22
9	389	1.54
10	480	1.90

These parameters enable us to select a suitable pump. In our case a high-pressure displacement pump (volume 500 L/min) has to be used.

The actual dynamic pressure of destruction V_2 can be calculated using formulas (7)–(9).

Basing on Q_2 = 500 L/min and d_0 = 10 mm, the actual dynamic pressure of destruction V_2 is calculated to be 106 m/s.

If the above conditions are met, the amount of broken oil shale can be determined by the pressure and the amount of water directed into the drilling holes. The specific water consumption is divided into two parts: the first part cuts and crushes the ore, and the other one makes the ore to collapse. Effect of borehole hydraulic mining depends on the properties of oil shale, water pressure and some other factors. The maximum amount of broken oil shale was determined by the following formula:

$$\Pi \max = \frac{12 \cdot D_d^2 \cdot H_0^{0.5} \cdot (P_0 - P_{cr}) \cdot 10^4}{\varepsilon} \, [\mathrm{m}^3 \cdot \mathrm{h}^{-1}], \tag{10}$$

where D_d – the radius of water jet; ε – empiric coefficient characterizing specific resistance to breakage (for oil shale, weakly bond sediment $\varepsilon = 10$); H_0 – depth of hydromonitors exploitation (m); P_0 – starting pressure of water; P_{cr} – critical pressure needed for breaking sliding resistance of oil shale (MPa). Assuming that we are drilling Nong'an oil shale whose overburden strata are sandstone and shale, the parameters of oil shale seam in Nong'an are: depth 235 m, the hydraulic pressure of work exceeds 10 MPa, the concentration of slurry (rock:water) 1/6–1/1. The cutting tool could reach 1.5–2.5 m. The thickness of the seam is 5 m. Considering the actual dynamic pressure of destruction V_2 106 m/s, the maximum amount of broken oil shale was calculated to be 200 m^3/h.

The results of the present work enabled us to design a flow sheet for borehole hydraulic mining. The maximum flow velocity for dynamic pressure of destruction calculated for the flow sheet is 300 m/s. So the most dangerous depth is expected to reach 450 m. Next, the experiments of borehole hydraulic mining will be done.

5. Conclusions

1. Physical and mechanical properties, weathering coefficient, rock mass integrity and series of other parameters for Nong'an oil shale in both horizontal bedding orientation and vertical bedding direction were determined and compared. Oil shale of Nong'an deposit belongs to slightly weathered and relatively complete rocks. No matter in what direction of bedding, the strength of oil shale seam was $\sigma_{compressive\ strength} > \sigma_{shearing\ strength} > \sigma_{tensile\ strength}$. The parameters of horizontal bedding including tensile strength, compressive strength, rock mass integrity and dynamic elastic modulus were greater than those of vertical bedding, while shear strength and weathering coefficient of vertical bedding were greater than those of the horizontal bedding.

2. The direction for borehole hydraulic mining for Nong'an oil shale was selected. The vertical bedding direction to break oil shale was considered to be better, because strength in this direction is low, rock mass integrity poor, and the degree of weathering more pronounced. Besides, at choosing the mode of hydraulic crushing, tensile fracturing should be chosen, as tensile strength of Nong'an oil shale was less than other strengths.

3. Technological parameters for borehole hydraulic mining of Nong'an oil shale were calculated. The minimum flow velocities for dynamic pressure of destruction were $V_{r\ \mathrm{horizontal\ bedding\ orientation}}$ = 86.3 m/s, $V_{r\ \mathrm{vertical\ bedding\ direction}}$ = 101.8 m/s. The primary decision was to use a high-pressure displacement pump (500 L/min, nozzle diameter 10 mm, and the actual dynamic pressure of destruction 106 m/s). The maximum amount of broken oil shale was calculated to be 200 m^3/h.

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