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EXPERIENCE OF GEOTECHNICAL CORE LOGGING OF BOREHOLE ENVIRONMENT: A CASE-STUDY OF CARBONATE ROCKS

Typical reservoirs of high-gravity oil come to depletion at this time and oil production slows. Currently, enhanced oil recovery technologies are being developed to extract scavenger oil from jointed carbonate reservoirs. Extraction of hydrocarbons from such reservoirs is connected with integrated investigation of rocks, including geomechanical research. This article describes assessment of horizontal stress values in borehole environment on the basis of geomechanical modeling. The values of stresses depend on systems of joints in carbonate reservoirs under varying stress tensor. The object of research is oil-filled jointed carbonate reservoirs. The scope of the research included the stress–strain analysis of carbonate reservoirs fractured by systems of joints extracted from the geotechnical logging of core. Using 3D finite-element model built in Midas GTS NX, numerical models of different areas in borehole environment are developed.

Keywords: *jointed reservoirs, carbonate rocks, lab-scale core investigation, geotechnical core logging, systems of joints, physical and mechanical properties, numerical modeling*
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Introduction

The petroleum industry is a key player in the Russian economy. Efficient oil development and production requires comprehensive geotechnical engineering. This article discusses experience of geotechnical logging of carbonate core taken in the oil-filled strata of reservoirs.

The accomplished experimental works allowed certain quantitative geotechnical estimation of rocks in the oil-filled strata, namely [1]:

- jointing of rocks was estimated using geological data obtained from drilling, and from structural geological and geotechnical analyses of core more than 100 m in total length;
- the quantitative and qualitative indexes and characteristics of rocks such as Barton's Q-system, Bieniawski's RMR values, Geological Strength Index GSI (Hoek's system) were determined [1–7] using geomechanical program RSData [7, 8];
- spatial orientation of joints relative to core axis was determined using the geotechnical evaluation results;
- the rock mass quality was assessed using the indexes Q, GSI and RMR.

Such initial information is a framework for the further determination and analysis of rock density and breakdown pressure in reservoirs [9–12]. It provides more accurate and reliable results, which is critical for the well-founded decision-making during oil field development [13–18].

In this manner, geotechnical logging of carbonate rock cores from reservoirs 301–303 in the Romashkino oil field has a practical significance and is applicable in design and planning of oil field development and infrastructure.

Application of the proposed procedure of geotechnical core logging made it possible to assess jointing in a large volume of core, up to some tens of meters in length, and, accordingly enabled reduction in labor cost of experimental investigations.

Geotechnical core logging methodology

The integrated procedure of geotechnical logging of carbonate rock core includes a few stages:

Processing and analysis of core. Determination of basic geotechnical parameters of rocks.

Evaluation of mechanical parameters of rocks. Investigation of such mechanical parameters of carbonate rocks as strength, elasticity and plasticity is important for drilling and oil production planning.

Geotechnical evaluation of core followed the guidelines of the Geomechanical Assessment of Core [2].

The core analysis checked the integrity of core samples and their conformity with the geomechanical modeling requirements. Core samples were selected for various-type testing (**Fig. 1**), and damages of the core samples were recorded. On the whole, the core integrity was assessed as unsatisfactory.

Fig. 1. Core samples: borehole 37819, interval 852–857 m, Kuakbash site. The picture was taken on 16 March 2005

Determination of strength and deformation characteristics of jointed carbonate rocks used the geological reporting data and program RSData which provides calculation of the generalized Hoek–Brown Failure Criterion [3]. The strength and deformation characteristics were evaluated for all types of rocks in accordance with the lab-scale strength testing results later on used in the stress–strain assessment of rock mass.

The Rock Quality Designation (RQD) index was determined from the core fracture analysis. The fracture frequency FF was also assessed. The latter characteristic is sensitive both in a fairly solid rock mass (zero or a few fractures recorded) and in a heavily broken and fractured block rock mass.

The quality and stability assessment of the oil-filled strata used the RMR system [4] including such parameters and characteristics as uniaxial compression strength, RQD, joint spacing and joint alteration number.

The quantitative evaluation used the RMR and Q-system of rock mass quality quantification.

The rock mass quality evaluation by Barton used the Q-system [5, 6]. The values of the Q index were changed on a logarithmic scale in a range from 10^{-3} to 10^{3}, which was divided into nine categories of rock mass quality. The calculation of the Q index used such parameters and characteristics of

Table 1. Geotechnical logging of core from borehole

No.	Interval		Structure					Structure			Strength	Group 1 [J1]: 0°–30°					Group 2 [J2]: 31°–60°					Group 3 [J3]: 61°–90°				
	From, m	To, m	Rock Quality Designation (RQD), %	Fracture frequency FF per interval	Volumetric joint count Jv	Joint spacing, m	Number of joint systems	Lithology	Weathering	Watering	Strength (hard rocks)	Number of joints	Micro-roughness	Type of filling	Strength of filling	Opening / thickness of filling, mm	Number of joints	Micro-roughness	Type of filling / alteration of joint surfaces	Strength of filling	Opening / thickness of filling, mm	Number of joints	Micro-roughness	Type of filling / alteration of joint surfaces	Strength of filling	Opening / Thickness of filling, mm
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
1	851.0	852.0	70	9	16	96	1R	Limestone	V1	D	R3	–	–	–	–	–	2	US	C	NSF	NC	7	US	E	SSC	NC
2	852.0	853.0	61	7	20	217	3	Limestone	V0	D	R2	2	PR	C	SSF	NC	–	–	–	–	–	5	US	B	NON	NC
3	853.0	854.0	56	8	22	196	3	Limestone	V0	D	R2	1	PS	B	NON	NC	1	US	C	NSF	>5.0	6	PS	B	NON	NC
4	854.0	855.0	67	7	17	193	2	Limestone	V0	D	R4	–	–	–	–	–	–	–	–	–	–	7	US	B	NON	NC
5	855.0	856.0	94	5	6	275	1	Limestone	V0	D	R4	–	–	–	–	–	–	–	–	–	–	5	PS	C	NON	NC
6	856.0	857.0	80	6	12	204	2R	Limestone	V0	D	R4	–	–	–	–	–	1	UR	B	NON	1.0-5.0	5	US	C	NON	NC
7	857.0	858.0	46	12	26	173	2	Limestone	V1	D	R4	1	PS	B	NON	NC	–	–	–	–	–	11	PS	B	NON	NC
8	858.0	858.2	98	0	5	231	M	Limestone	V0	D	R4	–	–	–	–	-	–	–	–	–	–	нет	–2		–2	
9	858.2	858.7	–	–	–	317	CZ	BZ	VD	–2	–2	–	–	–	–	-	–	–	–	–	–	нет	–2		–2	
10	858.7	859.0	85	1	10	163	1	Limestone	V0	D	R3	–	–	–	–	-	–	–	–	–	–	1	PS	B	NON	NC
11	859.0	860.0	65	7	18	75	2R	Limestone	V1	D	R2	1	UR	B	NON	NC	1	UR	B	NON	NC	5	US	B	NON	1.0-5.0
12	860.0	861.0	60	10	20	137	3R	Dolomite	V1	D	R4	4	US	C	NSF	>5.0	–	–	–	–	–	6	IS	C	NSF	>5.0
13	861.0	862.0	73	8	15	96	2	Dolomite	V0	D	R3	–	–	–	–	–	1	IS	B	NSF	1.0-5.0	7	PS	C	NSF	NC
14	862.0	863.0	49	11	25	217	3	Dolomite	V0	D	R3	1	PS	A	NON	NC	–	–	–	–	–	10	US	C	NSF	NC
15	867.0	868.0	16	13	38	196	3	Limestone	V1	D	R4	1	US	B	NON	NC	1	PS	B	NON	NC	11	PS	B	NON	NC
16	868.0	869.0	82	6	11	193	2	Limestone	V1	D	R4	2	PS	B	NON	NC	–	–	–	–	–	4	IS	C	NON	NC
16*	868.49		82	6	11	193	2	Dolomite	V1	D	R4	2	PS	B	NON	NC	–	–	–	–	–	4	IS	C	NON	NC
17	869.0	870.0	97	5	5	275	1	Limestone	V2	D	R4	–	–	–	–		–	–	–	–	–	5	IS	C	NSF	NC
18	870.0	871.0	82	8	11	204	3	Limestone	V2	D	R4	1	US	D	NSM	1.0–5.0	1	IS	E	NON	NC	6	US	E	NON	NC
19	871.0	872.0	54	13	22	173	3	Limestone	V1	D	R4	–	–	–	–	–	2	US	E	NSF	>5.0	11	PS	B	NON	NC

rock mass stability as: RQD; number of systems of joints; joint roughness number; joint alteration number; joint water parameter; pore pressure [5].

The other stage of assessment of rock mass quality used the Geological Strength Index GSI with regard to the structure and jointing of rock mass, and transition from properties of an intact sample to properties of jointed rock mass in natural conditions by analogy with the Russian coefficient of structural weakening [7, 8]. The index GSI in the modified classification is divided into four categories. The values of GSI were determined from empirical formulas in terms of RQD, Bieniawski's RMR or Barton's Q-system [4–6].

The rating evaluation of the quality of the oil-filled strata included the geological logs on 15 boreholes and the laboratory test data on physical and mechanical properties determined in 60 samples of rocks.

The average values of the rating evaluation of the rock mass quality in terms of three geological engineering elements are compiled by way of illustration in **Table 1**.

Geotechnical core logging results

The rating evaluation of the quality of rocks involved processing of geological data from 27 boreholes and lab-scale testing results on physical and mechanical properties of 60 rock samples.

The outcome of the geotechnical logging and rock mass quality per lithological types in exploration borehole is given in **Tables 1** and **2**.

Numerical stress–strain modeling of borehole environment in oil-filled stratum

The geomechanical modeling and analysis used the set of data of geological reports on 15 boreholes, geotechnical logging of cores and lab-scale geomechanical tests of rock samples. The constructed models focused on the vertical and horizontal stresses, pore pressure and elastic strength of rocks in the borehole environment in the test reservoirs.

Vertical stress modeling

The first step in the geomechanical modeling was calculation of the vertical stress σ_v, MPa, using the direct method with regard to the average value of rock pressure as function of the average rock density γ, g/cm^3, and occurrence depth H, m. The vertical stress σ_v is given by:

$$\sigma_v = \gamma, H, \text{ MPa}. \tag{1}$$

Pore pressure modeling

The second step was calculation of the pore pressure p_0, MPa, which was assumed to be equal to the hydrostatic pressure and was set as the pore pressure gradient grad p_0 = 0.013 MPa/m. For the types of rocks tested, p_0 was obtained using an indirect method, namely, common Eaton's method [9, 10].

Modeling minimal and maximal horizontal stresses

The boundary conditions in the model were set in terms of the horizontal stresses found from Eaton's equation. In hydraulic fracture mechanics described by M. J. Economides, the minimal horizontal stress $\sigma_{h\min}$, MPa, is presented as Eaton's equation (2) [11] which includes, among other things, the pore pressure as well [12]:

$$\sigma_{h\min} = \left(\frac{PR}{1 - pr}\right)(\sigma_v - p_0) + p_{res}, \text{ MPa}, \tag{2}$$

where $\sigma_{h\min}$ is the minimal horizontal stress, MPa; σ_v is the vertical stress, MPa; p_0 is the pore pressure, MPa; PR is Poisson's ratio.

For the conditions of the geomechanical model, the maximal horizontal stress $\sigma_{h\max}$ is determined as follows:

$$\sigma_{h\max} = 1.1\sigma_{h\min}, \text{ MPa}. \tag{3}$$

Table 2. Rating evaluation of core from borehole by Q-system (Barton)

No.	From, m	To, m	Interval, m	Rock	RQD, %	Strength	System of joints	Jn	Jr	Ja	Q′	GSI by Q′
	1	2	3	4	5	6	7	8	9	10	11	13
1	851.0	852.0	1.0	Limestone	70	R3	1R	3	2	4	11.72	52.48
2	852.0	853.0	1.0	Limestone	61	R2	3	9	2	1	13.56	65.17
3	853.0	854.0	1.0	Limestone	56	R2	3	9	1	1	6.17	53.75
4	854.0	855.0	1.0	Limestone	67	R4	2	4	2	1	33.35	68.02
5	855.0	856.0	1.0	Limestone	94	R4	1	2	1	2	23.55	64.43
6	856.0	857.0	1.0	Limestone	80	R4	2R	6	2	2	13.33	66.00
7	857.0	858.0	1.0	Limestone	46	R4	2	4	1	1	11.53	49.05
8	858.0	858.2	0,2	Limestone	98	R4	M	0,5	4	3	260.00	78.46
9	858.2	858.7	0,5	BZ	0	–2	CZ	20	-	-	-	-
10	858.7	859.0	0,3	Limestone	85	R3	1	2	1	2	21.25	59.83
11	859.0	860.0	1.0	Limestone	65	R2	2R	6	2	2	10.83	58.50
12	860,0	861.0	1.0	Dolomite	60	R4	3R	12	3	2	7.44	60.95
13	861.0	862.0	1.0	Dolomite	73	R3	2	4	1	2	9.06	53.58
14	862.0	863.0	1.0	Dolomite	49	R3	3	9	2	2	5.40	50.30
15	867.0	868.0	1.0	Limestone	16	R4	3	9	1	2	0.89	25.33
16	868.0	869.0	1.0	Limestone	82	R4	2	4	3	2	30.56	71.95
16*	868.49			Dolomite	82	R4*	2	4	3	2	30.56*	71.95*
17	869.0	870.0	1.0	Limestone	97	R4	1	2	3	2	72.60	79.60
18	870.0	871.0	1.0	Limestone	82	R4	3	9	2	2	9.12	67.05
19	871.0	872.0	1.0	Limestone	54	R4	3	9	1	2	3.00	44.33

Table 3. Strength and deformation characteristics of jointed rock mass from estimates of core

Parameter	Rock mass (RMR)	Rock mass (Q)
Depth, m	868.49	
Lithology	Dolomite	
Properties of sample		
Density, kg/m^3	2390	
Bulk density, kg/m^3	2396–2464	
Ultimate tensile strength UTS, MPa	5.77	
Ultimate compressive strength UCS σ_c, MPa	66.41	
Geological Strength Index GSI	61.75	71.95
Index of type of rock (lithology, genesis), m	9	
Elasticity modulus (dynamic) E, GPa	45.73–53.4 49.565 (averaged)	
Poisson's ratio	0.29–0.3	
Internal friction angle,°	31.98	
Cohesion, MPa	18.41	
Hoek–Brown criterion		
m_b	2.296	3.305
s	0.0143	0.0443
a	0.503	0.501
Mohr–Coulomb criterion		
Cohesion C, MPa	3.920	4.847
Internal friction angle φ, deg	33.04	35.91
Jointed rock mass properties		
Uniaxial compression strength σ_c, MPa	7.848	13.928
Triaxial compression strength $\sigma_{c.t}$, MPa	14.450	18.987
Deformation modulus E_{rm}, MPa	27740.99	38050.87

Geomechanical assessment of rocks

Geomechanical modeling of the borehole environment in an oil reservoir should include the elastic properties and strength characteristics of rocks. The elastic properties represented by the Young modulus, shear modulus, volumetric modulus, the Biot coefficient and Poisson's ratio are obtained from laboratory scale measurements. An illustration of the parameters of the dynamic and static geomechanical properties determined in laboratory tests is given in **Table 3**.

Approach to stress–strain assessment of rock mass in borehole environment

The impact of the orientation of fractures on the stress–strain behavior of rock mass in the borehole environment was assessed by varying characteristics of systems of joints in the Jointed Rock models in Midas GTS NX software. The modeling used the finite element method in elastoplasticity with regard to the Hoek–Brown criterion in efficient program RS2.

The model images averaged borehole environment conditions typical of oil reserves enclosed in jointed carbonate rock mass. In modeling, the angles and directions of joints from the geotechnical core estimation were varied. The joint condition described with the index J_C was kept constant. The values of the stresses and displacements at the borehole boundary, in its neighborhood and at a distance from it were analyzed at different ratios of the mentioned factors.

The model represents a cube (**Fig. 2**) composed of three layers: 1) the top is overburden rocks; 2) the middle is the test interval of an oil-filled stratum; 3) the bottom is underlying rock strata.

The variation in the parameters of jointing from the geotechnical core estimations is described in **Table 4**.

The multivariant modeling results and the stress pattern in the borehole environment are depicted in **Figs. 3** and **4**.

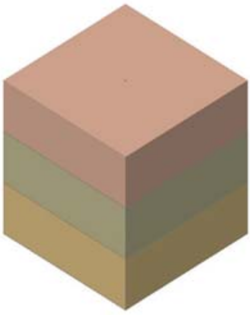

Fig. 2. 3D model of test area 9×9×9 m for numerical modeling

Table 4. Elastic properties and characteristics of systems of joints in 3D modeling

Type of rock	Density γ, g/cm^3	Elastic modulus E, GPa	Poisson's ratio ν	Shear modulus G, GPa	Number of systems of joints, n	Incidence angle $\alpha_{1i}{}^0$ / azimuth angle $\alpha_{2i}{}^0$ of i-th system of joints			Cohesion C, MPa, in i-th system of joints			Internal friction angle φ^0		
Overlying layer						1st system	2nd system	3rd system	1st system	2nd system	3rd system	1st system	2nd system	3rd system
Dolomite	2.6	10.625	0.29	4.118	2	Variant 1								
						15/90	75/180	–	0.2	0.2	–	25	25	–
						Variant 2								
						30/90	90/180	–	0.2	0.2	–	25	25	–
						Variant 3								
						1/90	61/180	–	0.2	0.2	–	25	25	–
Test layer														
Limestone	2.7	45.73	0.29	17.725	2	Variant 1								
						15/90	75/180	–	0.2	0.2	–	25	25	–
						Variant 2								
						30/90	90/180		0.2	0.2	–	25	25	–
						Variant 3								
						1/90	61/180		0.2	0.2	–	25	25	–
Underlying layer														
Mudstone	2.6	22.5	0.29	8.721	3	Variant 1								
						45/90	75/135	75/180	0.375	0.375	0.375	37.5	37.5	37.5
						Variant 2								
						60/90	90/135	90/180	0.375	0.375	0.375	37.5	37.5	37.5
						Variant 3								
						31/90	61/135	61/180	0.375	0.375	0.375	37.5	37.5	37.5

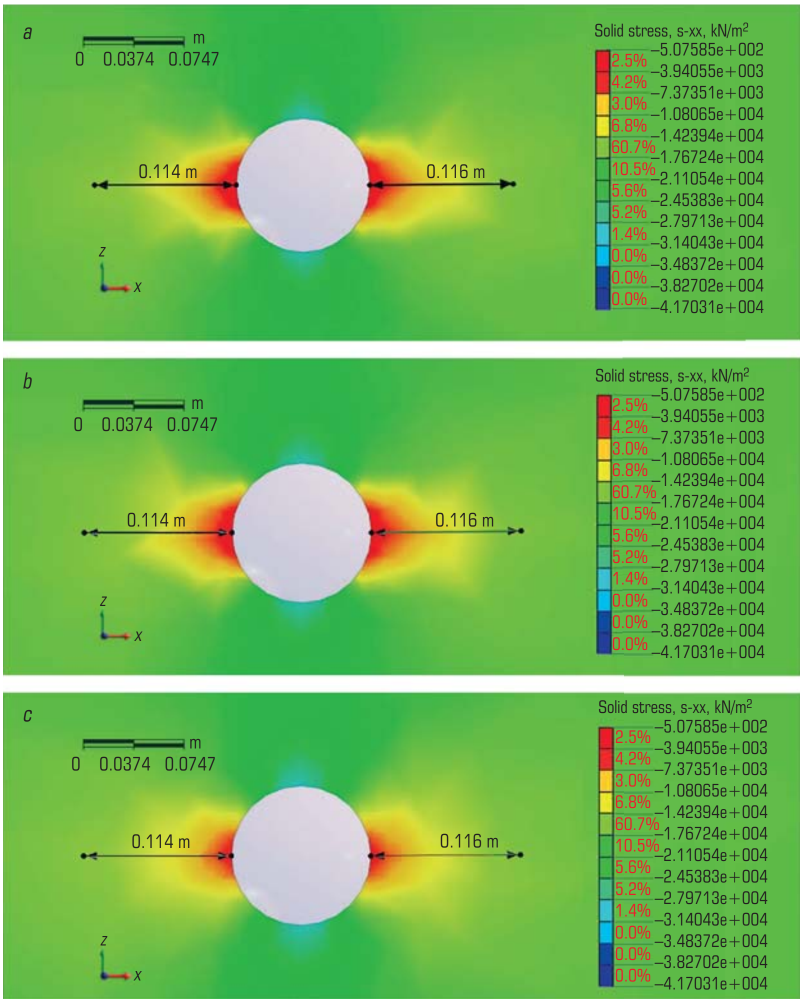

Fig. 3. Horizontal stresses along X-axis (cross-section). Variant 1:
a – overlying layer; *b* – test (middle) layer; *c* – underlying layer

Results and discussion

Discussion of the results obtained in geotechnical logging of cores taken in oil-filled strata of reservoir rocks based on their geomechanical documentation is founded on the integrated analysis of the research findings.

The evaluation of the main properties of rocks, such as their strength and deformation characteristics, and tendency to fracture;

The analysis of the oil content of rocks, which is critical in defining the scope of geotechnical core logging;

The study of the structural features of rocks to understand their geomechanical properties and to predict potential geomechanical processes;

The geotechnical research results are:

The found and analyzed interconnection between the geological and geomechanical parameters, which helps get a deeper insight into the physical processes in rocks to optimize hydrocarbon production.

Using the 3D model built using the finite element method, the stress–strain behavior has been assessed in the borehole environment in jointed rock mass. The influence of the jointing parameters on the stress–strain behavior of rocks in the borehole environment is additionally estimated [11, 12].

Conclusions

The accomplished geotechnical logging of cores of carbonate rocks enclosing provided information on the geology and physical and mechanical properties of these rocks. It is planned to use these data in development of an oil production strategy, optimization of drilling and in improvement of operating safety.

The geotechnical logging of carbonate rock cores is a critical stage in research and development of oil reservoirs. The experience and findings of the research on enclosing rock mass in the Kuakbash site of the Romashkino field

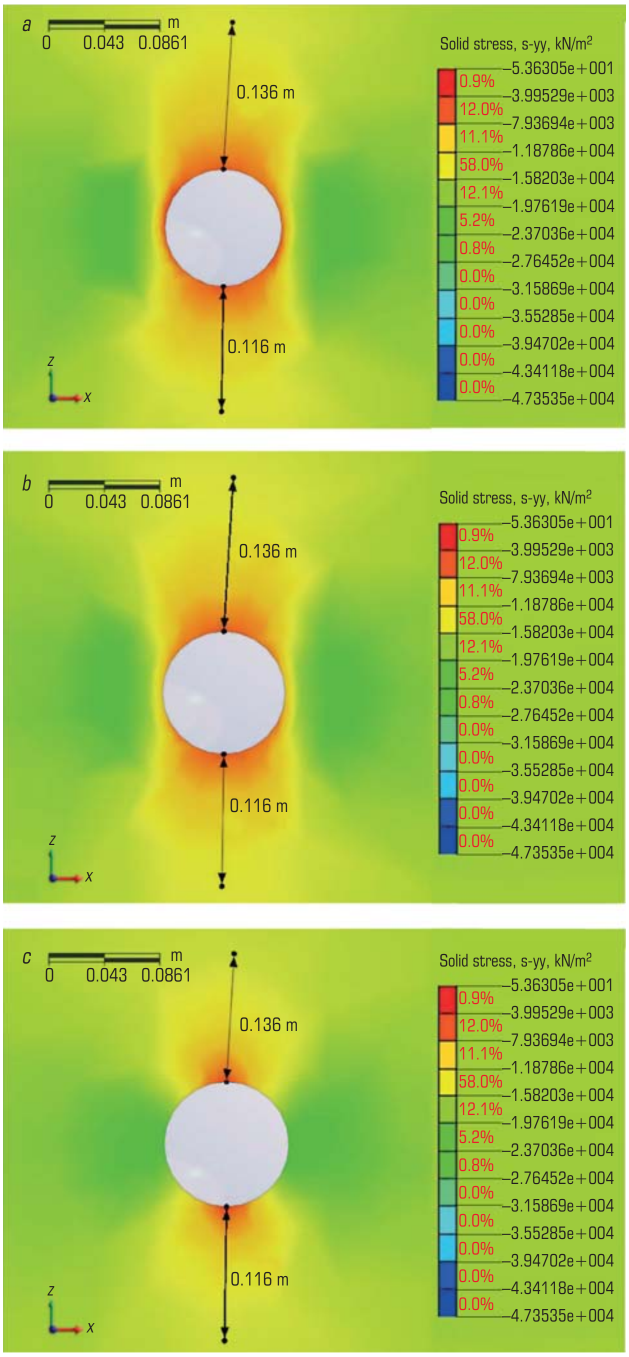

Fig. 4. Horizontal stresses along Y-axis (cross-section). Variant 1:
a – overlying layer; *b* – test (middle) layer; *c* – underlying layer

are applicable in other projects toward enhanced efficiency and safety of oil recovery.

The implemented analysis and discussion of the results allows concluding that geomechanical properties of reservoir rocks have influence on all processes in oil recovery, and enables recommendations on oil recovery optimization based on the geotechnical logging and classification of cores. All these provide a framework for the stress–strain forecasting based on numerical modeling, and for constructing a 3D geomechanical model.

The results of the geotechnical core logging are usable in assessment of fracture porosity and permeability from the correlation with the fracture opening and average spacing.

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