Geomechanical Modeling for Creating New Technologies of Deep Hydrocarbon Fields Development

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Abstract— **The paper presents the results of the experimental investigation of the rock physical properties in relation to issues of creating scientific fundamentals for new hydrocarbon production technologies. Nowadays easily accessible deposits of oil and gas which lies at depths of 2-3 km are gradually being depleted. The production of hydrocarbons from unconventional sources becomes all the more urgent. These include shale gas and oil, Arctic hydrocarbon resources, gas hydrates, coal bed methane, oil and gas from deep horizons. The development of such deposits requires the creation of new technologies. The knowledge of mechanical and filtration properties of rocks lying at great depths is needed for creation of the new oil production technologies. The investigation of the dependence of well stability and permeability of rocks on the stress-strain state which is determined by the pressure in the well and its bottom hole design in conditions of high rock pressure is required also. For the first time the tests of reservoir rocks from the depths of more than 6 km were carried out on the true triaxial load system. The real conditions that occur in the vicinity of the borehole for various bottom designs at lowering pressure were experimentally simulated on the unique experimental facility, Triaxial Independent Load Test System built in the Institute for Problems in Mechanics of the Russian Academy of Science. It is found that the possibility to improve the production rate of a well by increasing pressure drawdown in a well exists despite the low permeability and high strength of such rocks.**

Index Terms— **deep reservoirs, rock, well, the test facility, deformations, stresses, strength, elastic moduli.**

I. INTRODUCTION

Increasingly urgent need to expand the resource base of hydrocarbons arises due to the depletion of large and accessible oil and gas fields. The shale oil and gas, Arctic hydrocarbon stocks, oil from deep horizons and others can become new sources. New technologies are required to their development. Efficient low-cost technologies can be created on the basis of geomechanical approach, i.e. through the use of a huge elastic energy stored in the rock mass due to rock pressure.

A characteristic feature of rocks is a significant dependence of their stress-strain properties on the stress condition type and stresses value. Therefore, to solve the geomechanical problems related to the creation of new technologies for the deep-seated deposits development, providing the wellbores stability at great depths and many others, it is important to know the strain characteristics of rocks under the actual stresses in the vicinity of deep wells. Such a possibility is provided by the Triaxial Independent Load Test System (TILTS) (see Fig. 1) built in IPMech RAS [1].

II. EXPERIMENTAL FACILITY AND LOAD PROGRAMS FOR SPECIMENS

TILTS is a unique test facility that allows to study the strain, strength and filtration characteristics of rocks by testing cubic specimens of size 40 or 50 mm. The TILTS is equipped with automatic permeability measurement system, which allows studying the characteristics of rocks permeability versus magnitude and type of effective stresses.

The facility allows independent loading of cubic rock specimens in three axes, which is possible with an original kinematic structure used in the design of a load assembly. This offers the possibility to recreate, during the tests, any stress conditions that appear in the bottomhole zone when the well is being drilled, completed, or operated and to study their effect on filtration properties of rocks.

The experiments on determination of strain, strength and filtration characteristics for the core materials of four lithotypes (argillite, aleurolite, quartz sandstone, and dolomite) taken from depths of more than 6 km of the exploratory wells 1 and 2, drilled at the Astrakhan gas condensate field of Public Joint Stock Company Gazprom have been carried out. 7 cubic specimens with the edge 40 mm are made from this core materials.

Prior to the TILTS testing, the velocities of longitudinal elastic waves propagation along three axes of all specimens are measured by using of special equipment. Velocities measured for sandstone and dolomite appear to be approximately the same in all directions. So, for one of the sandstone specimens (depth 6058 m) velocity along the vertical axis of the core, i.e. perpendicular to the bedding plane, is 5.00 km/s and velocities in the plane are 5.20 and 5.30 km/s.

At the same time the velocities for the argillite and aleurolite specimens in the bedding plane are measured twice larger than one along the core axis. The velocity for the argillite specimen No. A 2-2 (depth 6556 m) in horizontal plane is 4.40 km/s in the bedding plane, and one along the core axis is 1.85 km/s.

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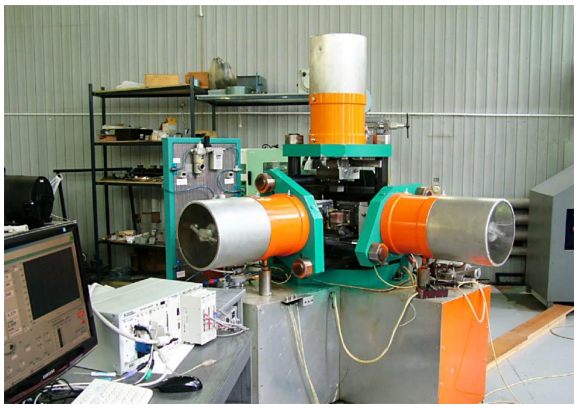

Fig. 1. Triaxial Independent Load Test System (TILTS)

So sandstone and dolomite specimens have elastic properties close to isotropic and by contrast the argillite and aleurolite specimens have layered structure and have transversely isotropic properties.

The tests are performed on load programs, simulating two types of stress-strain state: the generalized shear and the generalized tension. The generalized shear is a superposition of uniform hydrostatic compression and stress state, which occurs when one principal stress grows, other decreases, and third is held constant, while the average pressure also remains constant (see Fig. 2). The Lode parameter [2] corresponding to this stress state equals to '0' as for pure plane shear. The generalized tension is a superposition of uniform hydrostatic compression and stress state, which occurs when two principal stresses grow, and third one decreases, while the average pressure remains constant (Fig. 3). The Lode parameter for this case is equal to '+1', as under uniaxial tension.

The values σ_1, σ_2, σ_3 (in Fig. 2, 3) correspond to the stresses applied on the axes of TILTS. The monotonically increasing stress σ_2 is the load parameter. The specific choice of these two testing programs is due to the fact that they correspond to the real stress conditions in the reservoir for two basic bottom-hole designs [3]: generalized shear (Fig. 2) is realized in the vicinity of an open borehole or the perforation when the pressure in the well decreases (i.e. pressure drawdown increases) and generalized tension (Fig. 3) occurs in the vicinity of the spherical tip of the perforation when the pressure in the well decreases.

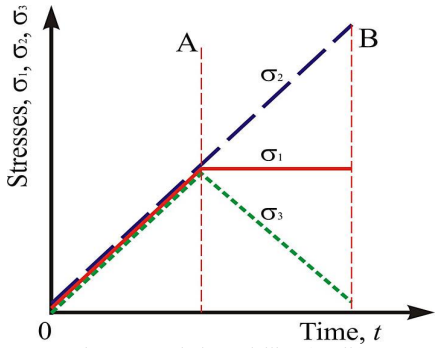

Fig. 2. Borehole modelling ('well').

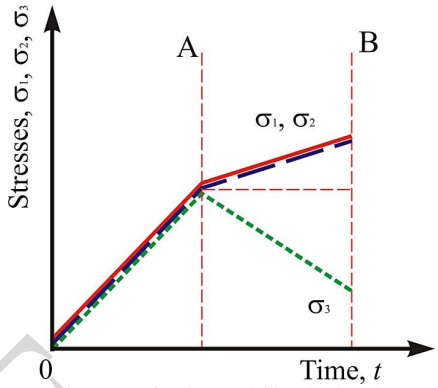

Fig. 3. Perforation modelling ('sphere').

Effective stresses (stresses acting on the soil framework) in the vicinity of a well (Fig. 4) as the Lame's problem solution [2, 4] are

$$\sigma_r = -(q + p_c)(R_c / r)^2 + q, \quad (1)$$

$$\sigma_\varphi = (q + p_c)(R_c / r)^2 + q, \quad (2)$$

$$\sigma_z = q, \quad (3)$$

where $q = -\gamma h$ – rock pressure at the chosen depth, γ – average rock unit weight, h – formation depth, p_c – bottom-hole pressure ($p_c > 0$), R_c – bottom-hole radius, r – distance from the borehole axis, (compressing stress values are considered negative).

When $r = R_c$, it can be found from (1) – (3)

$$\sigma_r = -p_c, \ \sigma_\varphi = 2q + p_c, \ \sigma_z = q \quad (4)$$

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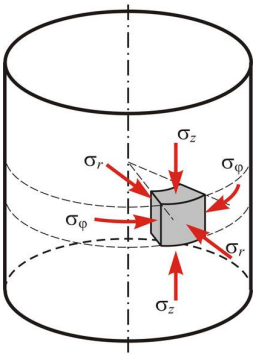

Fig. 4. Stresses in the vicinity of well.

The expressions for effective stresses in the vicinity of sphere (Fig. 5) are respectively:

$$\sigma_r = -(q + p_c)(R_c / r)^2 + q, \quad (5)$$

$$\sigma_{\theta,\varphi} = \frac{1}{2}(q + p_c)(R_c / r)^2 + q. \quad (6)$$

On the perforation wall (when $r = R_c$)

$$\sigma_r = -p_c, \ \sigma_{\theta,\varphi} = \frac{3}{2}q + \frac{1}{2}p_c. \quad (7)$$

During the both load programs the specimens are first driven to the conditions of uniform overall compression, in which the rocks are supposed to be found at the depth of core capture before the well is drilled out (Fig. 2, 3, section OA, at the point A $\sigma_i = q$). Then the specimens behavior is studied under the change of stresses in the vicinity of the borehole when the pressure at the well bottom changes (Fig. 2, 3, section AB).

The correspondence of stresses applied to the faces of specimen to stress components acting in the vicinity of the borehole during the load program 'well' are $\sigma_1 - \sigma_z$, $\sigma_2 - \sigma_\varphi$, $\sigma_3 - \sigma_r$. During the load program 'sphere' the correspondence is $\sigma_1 - \sigma_\varphi$, $\sigma_2 - \sigma_\theta$, $\sigma_3 - \sigma_r$.

III. ROCK SPECIMENS TEST RESULTS

The test results for two specimens cut from the same piece of core from the well 2 are presented in Fig. 6 –9. The specimen is a fine-grained sandstone, depth of coring is 6058 m, which corresponds to the magnitude of the rock pressure of about 140 MPa, if $\gamma = 2.3 \cdot 10^3$ kg/m^3. The initial permeability is equal to zero.

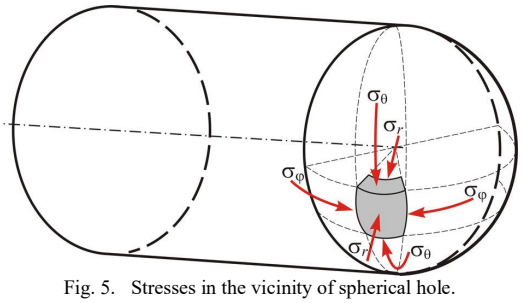

Fig. 5. Stresses in the vicinity of spherical hole.

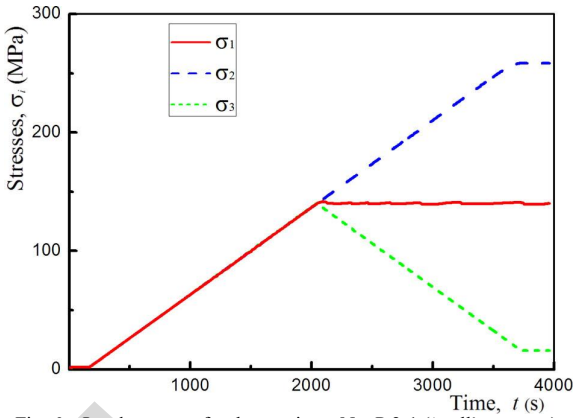

Fig. 6. Load program for the specimen No. P 2-1 ('well' program).

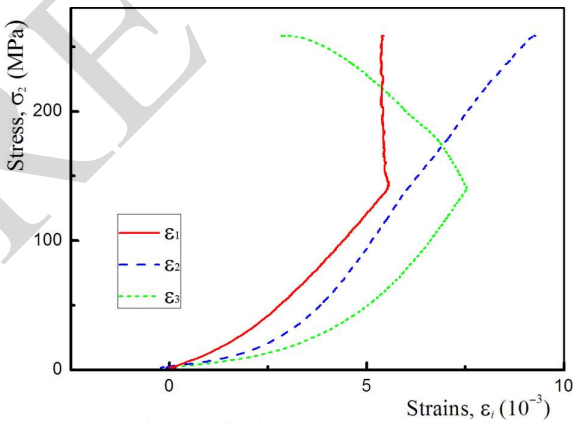

Fig. 7. Stress-strain curves for the specimen No. P 2-1 ('well' program).

The conditions that occur in the vicinity of uncased well, when the pressure on its bottom decreases, are simulated during the test of the specimen No. P 2-1 (see Fig. 6, 7). The conditions that occur in the vicinity of the perforation tip (hemisphere), when the bottom pressure decreases, are simulated during the test of the specimen No. P 2-2 (see Fig. 8, 9).

The illustrations show that the specimen No. P 2-1 is deformed almost elastically up to the maximum possible decrease of pressure on the bottom hole, whereas the specimen No. P 2-2 moved to the stage of inelastic deformation at the strain value corresponding to the well pressure of approximately 150 MPa and has been heavily deformed and soon destroyed.The rock specimen No. P 2-2 after the test is shown in Fig. 10, where it can be easily seen that the specimen

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disintegrated by macroscopic fracture settled in the plane perpendicular to the direction of the lowest compressing stress. At the same time the permeability of the specimen which initially is absent in this direction has abruptly increased on the disintegration stage of load test (Fig. 11).

A similar permeability pattern is observed in the test of argillite specimen No. A 2-2, but the character of fracture is distinct. The specimen is fractured in the planes perpendicular to the direction of the lowest compressing stress, but with more than one macro cracks developed in the bedding planes. Permeability of the specimen along the bedding planes direction is also increased significantly (Fig. 12).

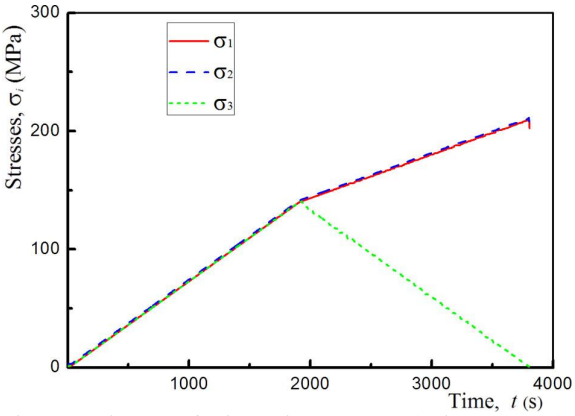

Fig. 8. Load program for the specimen No. P 2-2 ('sphere' program).

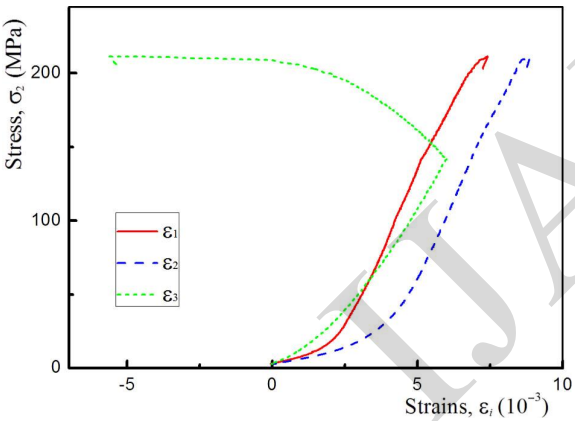

Fig. 9. Stress-strain curves for the specimen No. P 2-2 ('sphere' program).



Fig. 10. Specimen No. P 2-2 after the test.

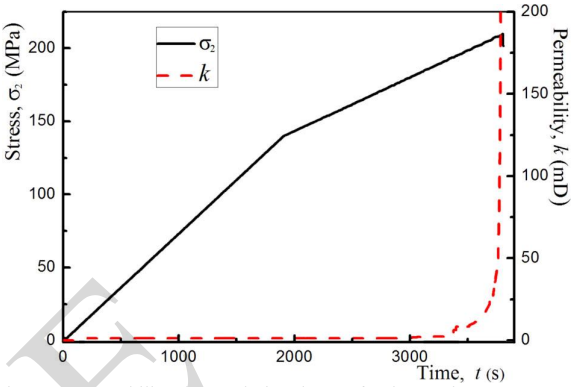

Fig. 11. Permeability change during the test for the specimen No. P 2-2.



Fig. 12. Specimen No. A 2-2 after the test.

Elastic moduli are calculated using the stress-strain curves obtained for the tested rocks such as Young's moduli in the bedding planes and Poisson's ratios in the perpendicular direction. The data obtained are given in Table. 1.

Table I. Elastic moduli of tested rocks

Specimen No.	Well	Depth, m	Lithotype	Young's modulus, 10^4 MPa	Poisson's ratio
A 1-1	1	6247	argillite	3.10	0.13
AL-1	1	6570	aleurolite	2.75	0.17
A 2-1	2	6556	argillite	1.90	0.12

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Specimen No.	Well	Depth, m	Lithotype	Young's modulus, 10^4 MPa	Poisson's ratio
A 2-2	2	6556	argillite	2.30	0.14
P 2-1	2	6058	quartz sandstone	2.80	0.12
P 2-2	2	6058	quartz sandstone	3.70	0.12
D 2-1	2	5751	dolomite	4.1	0.12

IV. CONCLUSION

The complex load test of the rocks from depths exceeding 6 km are carried out for the first time. The tests have shown that various rocks of different lithological composition are characterized by high strength and low permeability.

The basic result of the performed research is the fundamental possibility for the rocks lying at great depths and affected by extremely high compressive stresses to significantly increase their permeability which initially is low. The purpose can be achieved in result of fracturing and disintegration of the rock in the reservoir by reducing the well pressure to a certain value, and choice the geometry of the bottom hole.

The obtained results are of great importance for solving problems connected to creating effective technologies for the development of the deeper deposits, as well as to reducing risks during drilling and operation of wells.

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