Oil and Gas

UDC 622.24

DETERMINING THE STABILITY OF THE BOREHOLE WALLS AT DRILLING INTERVALS OF LOOSELY COUPLED ROCKS CONSIDERING ZENITH ANGLE

Pavel A. BLINOV
Saint-Petersburg Mining University, Saint-Petersburg, Russia

During development of drilling projects, a whole array of data is needed considering the properties of rocks and the conditions of their bedding. Accounting for geomechanical processes occurring in the near-wellbore zone allows avoiding many complications associated with the violation of the wellbore walls stability at all stages of its construction and operation. Technological and technical factors such as vibration and rotation of the drilling string, formation of launders during the descent and ascent of the assembly, pressure pulsation during the start and stop of pumps, hydrostatic and hydrodynamic pressure of the drilling fluid, its composition and properties, have a great influence on the stress-strain state of the medium opened by the well. The washing fluid circulating in the well should provide back-pressure to the reservoir, not interact with the rocks chemically, colmatage channels in porous and fractured rocks, preventing penetration of the mud into the medium, by creating an impermeable barrier at drilling clay seams that are prone to swelling, cracking, etc.

The article discusses the method for determining the stability of the directed well walls, taking into account the penetration of drilling mud into the pores and fractures of rocks. The technique will allow adjusting the zenith angle of the well during the workout of an unstable interval at the design stage, or selecting a drilling fluid composition to ensure fail-safe drilling.

***Kew words*:** drilling; drilling mud; strain condition of the rocks; stability of the wellbore; drilling mud filtrate

***How to cite this article*:** Blinov P.A. Determining the Stability of the Borehole Walls at Drilling Intervals of Loosely Coupled Rocks Considering Zenith Angle. Journal of Mining Institute. 2019. Vol. 236, p. 172-179. DOI: 10.31897/PMI.2019.2.172

Introduction. In the past five years, in Russia, rotor-driven controlled systems have been used as a technical and technological solution aimed at reducing accidents and improving the quality of well construction with a large deviation from the vertical – Extended Reach Drilling (ERD). They make it possible to use directed drilling along the entire length of the well [6]. At trajectory designing, the initial and final coordinates of the curved and obliquely rectilinear (tangential) intervals are of great importance. The length of the vertical and the coordinates of the tangential intervals with large distance, their connection with the intervals of the zenith angle change impose restrictions associated primarily with the possibility of drilling, completing, developing and choosing the method of further well exploitation [11].

The rapidly developing segment of oil and gas services is the construction of multilateral and multihole wells. Multilateral drilling technique Technology Advancement for Multi-Laterals (TAML) allows increasing the profitability of oil and gas production, which is of particular importance for the exploitation of deposits with hard-to-recover reserves, as well as for the fields in the final stages of development, whose share of the total number increases every year [11, 15]. Joint sections of the lateral and main wellbores are experiencing significant loads, which are directly dependent on the magnitude of the pressure drop on the structure from the side of the well and the rock. At the same time, high values of differential pressure create stresses in the metal of pipes, which are close to the yield point [11].

Modern technologies require reliable methods for predicting the stress state of the medium in the near-wellbore zone, taking into account the spatial position of a directional well. An important role is played by the drilling fluid in contact with the rock and penetrating deep into the reservoir at a considerable distance. The components included in its composition colmatage the pores and fractures, adsorb on the surface of the mineral grains, enter into a chemical reaction with them. As a result of this interaction, the walls of the well may lose stability, or vice versa – they will harden.

There are several methods for predicting the manifestations of rock pressure, each of which has certain advantages and disadvantages. The scope of one or another of them is limited to specific rock-geological and production-technical conditions, the possibility of obtaining and the degree of reliability of the necessary information, and at the stage of exploration and prospecting – the presence of such geological areas [4, 5, 8, 9].

Scientific studies to strengthen the wellbore are divided into two directions: the study of the chemical reagents' effect on the stability of the wellbore and the study of the colmatage effect of the well walls on the stressed state.

Statement of the problem. The efficiency of analytical methods for determining the manifestations of rock pressure depends on the choice of a rheological model that approximates a rock massif, and the accuracy of determining the properties of the rocks composing it. In engineering and analog methods, the real situation is taken into account to a greater degree [4, 5, 8, 9]. At present, the profiles of oil and gas wells are designed in specialized software, which with sufficient accuracy determine the stresses in the rocks, taking into account geophysical studies on the previously drilled wells. However, they do not take into account the effect of the drilling fluid. For this, empirical approaches to solving the problem are necessary, which limits their application to the conditions of a separate object or geological region.

Methodology. To determine the effect of mud filtrate on the stability of an inclined borehole, the following method is proposed, based on determining dependencies [16-20]: the filtration and durability characteristics of a rock on the dispersity of the drilling mud; the durability characteristics of the rock on the mud filtrate; the distribution of borehole wall stresses on the zenith angle of the well, taking into account the influence of drilling mud filtrate.

In order to identify the nature of the dependencies the following scheme of experimental work is proposed:

• Creating a bulk rock model: screening out the sand of a certain fraction; humidification and compacted tamping of sand in a special ring compatible with a Fann low-pressure filter press and Direct Shearand Vane Tests single-plane cut-off device; calculation of permeable channels' dimensions; calculation of porosity and permeability of the rock model.

• Selection of the basic drilling mud formulation: selection of drilling mud filler fractions (marble aggregate is used); assessment of the reagents' compatibility with the drilling mud base (sodium liquid glass, glycerin, latex, «Kometa-meteor» reagent KM-PVR17, Polydon-A) were used as the test reagents; determination of the tested reagents' concentration and their effect on the parameters of the drilling fluid.

• Filtration tests on a bulk rock model using a Fann low pressure filter press.

• Testing a rock sample on a single-plane cut-off after filtration of the drilling mud on the device Direct Shear and Vane Tests, determining the values of the internal friction angle and adhesion of the model.

• The calculation of the results considering stress state around the wellbore and the determination of the conditions, affecting the stability most.

To create a bulk model of rock quartz sand fraction of 200-385 microns and humidity of 20 % was selected. Since the model is formed by a strong tamping, the particles are packed tightly. The total porosity with this type of laying (laying angle 60°) is 25.99 %. Using analytical geometry, the pore channel diameter was calculated, depending on the particle size of $30.9 < d_{por} < 59.5$ μm. The permeability coefficient, calculated using the F.I.Kotyakov formula, is equal to 3.46 Darcy.

A polymer drilling mud with a density of 1200 kg/m^3 is used as the base solution. The technical result is a high moving and holding capacity of the drilling fluid, low filtration, relatively low consumption of reagents. Polymeric drilling solution for testing includes Duovis xanthan biopolymer, Pac HV and Pac LV polyanionic cellulose, inhibiting additive (test reagents), carbonate weighting agent of various fractions and water.

DOI: 10.31897/PMI.2019.2.172

Table 1

The dependence of the drilling fluid parameters on the dispersion of the filler

Drilling fluid parameters	The dispersion of the filler, μm			
	5	50	100	150
Water loss, cm^3/30 min	10	9	9	9
SSS 10 s, Pa	5	4	4	3
SSS 10 min, Pa	6	5	5	5
Plastic viscosity, mPa·s	20	17	17	19
DSS, Pa	23	19	19	18

Drilling fluid recipe, % by weight: Duovis – 0.1; PacHV – 0.2; PacLV – 0.2; $CaCO_3$ – 26.35 (up to a solution density of 1200 kg/m^3). To assess the dependence of the drilling fluid parameters on the dispersity of the filler, compositions with chalk fractions of 5; 50; 100; 150 μm were prepared.

The parameters of the drilling fluid measured on the devices Fann 35s and Fann low-pressure filter press are presented in Table 1.

As can be seen from the experimental data, chalk with a particle size of 5 μm most strongly affects the rheological parameters, and solutions with a filler dispersion of 50 and 100 μm have similar characteristics.

To determine the concentration of chemical reagents a base solution with a dispersity of 50 μm was used. Alternately, 1; 2; 3 % of the reagent was introduced into it and changes in the properties of the solution were observed.

Based on experimental data (Table 2) the following results were obtained:

• liquid glass reduces drilling mud viscosity by about 25 %; all rheological parameters are reduced, but the solution water loss decreases; with increasing concentration in solution, rheological parameters are restored;

• «Kometa-Meteor» reagent KM-PVR17 slightly reduces viscosity, static shear stress (SSS) and dynamic shear stress (DSS); water loss and plastic viscosity remain unchanged; with increasing concentration rheological parameters increase;

• latex increases all rheological parameters; water loss remains unchanged; with increasing concentration rheology increases;

• glycerol has little effect on the rheological parameters of the solution; with increasing concentration, they slightly increase;

• Polydon-A thickens the base solution, all rheological parameters increase with increasing reagent concentration, since it is a high molecular weight structurant; water loss remains unchanged.

Table 2

The dependence of the drilling mud parameters on concentration of reagents

Reagent	Concentration, %	Water loss, cm^3/30 min	SSS 10 s, Pa	SSS 10 min, Pa	Plastic viscosity, mPa·s	DSS, Pa
Liquid glass	1	8	3	5	12	12
	2	8	3	5	14	14
	3	8	3	5	17	15
Latex	1	9	4	5	20	19
	2	9	5	6	20	20
	3	9	5	6	21	21
Glycerol	1	9	4	5	17	17
	2	10	4	5	19	18
	3	10	4	5	18	18
KM-PVR17	1	9	3	4	16	15
	2	9	3	4	17	15
	3	9	4	5	17	15
Polydon-A	1	9	4	5	18	17
	2	9	4	5	18	19
	3	9	5	6	21	20

To assess the mud colmataging ability with filler additives of various fractions, filtration experiments were carried out through the bulk rock model on a Fann low-pressure filter press using a special ring. Excessive pressure was 0.1 MPa. The pore diameter of the sand model $30.9 < d_{por} < 59.5$ μm.

To calculate the filtration rate, the time and volume of the filtrate were monitored. According to the filtration rate, the time for the formation of a low-permeable mud cake can be set.

According to the experimental data of filtering solutions with different fractions, following conclusions can be drawn (Fig.1):

• Lowest filtration rate and the minimum volume of the filtrate has a solution with a chalk content of 150 microns dispersion. This indicates a good colmataging ability and high particle sedimentation rate. When using this fraction, a low-permeable barrier forms the earliest. The size of the marble aggregate particles are at least three times the size of permeable channels. The density of the filtrate is equal to the density of water - all marble aggregate settles on the mud cake and in the pores of permeable channels;

• Highest level of filtration is demonstrated by the solution with the content of the chalk fraction of 5 μm. Particles, many times smaller than the size of channels, do not block the pore space, do not cause colmatage effect. The moment of a sharp decrease in filtration rate is not observed. The filtrate density of 1100 kg/m^3 indicates that most of the particles contained in the solution can freely seep through the bulk model;

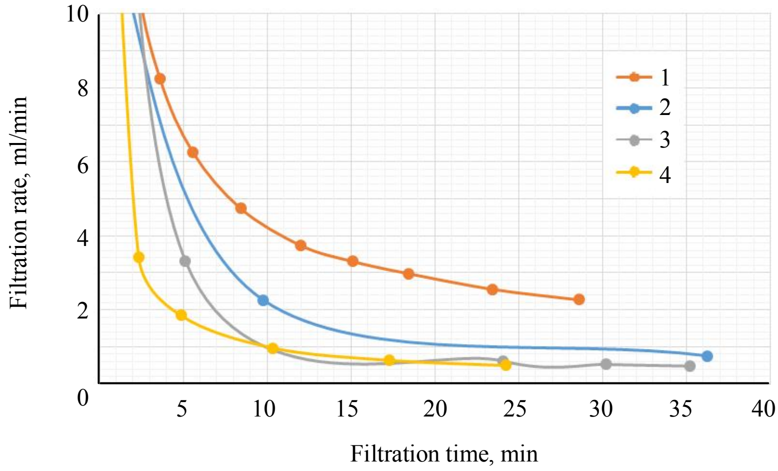

Fig.1. Dependence of the solutions filtration rate with different fractions on time
Fractions' size: 1 – 5 μm; 2 – 50; 3 – 100; 4 – 150

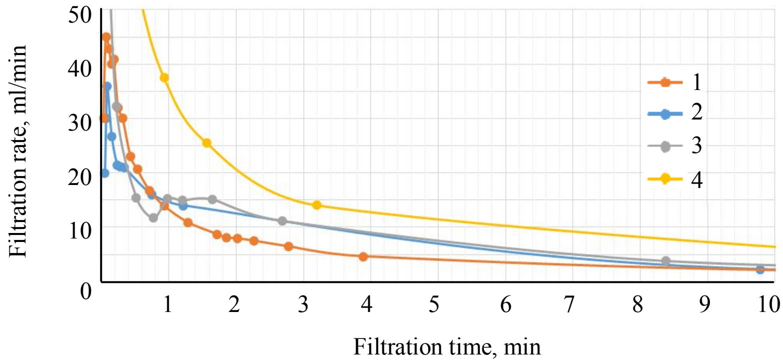

Fig.2. Dependence of the solutions filtration rate with different fractions on time
1 – without reagents; 2 – liquid glass; 3 – KM-PVR17; 4 – latex

• Solutions with a chalk fraction of 50 and 100 μm show approximately the same level of filtration. The moment of a sharp decrease in the filtration rate occurs at the same time – the period of the formation of a low-permeable cake is the same. The size of chalk particles varies from one to two diameters of permeable channels. The filtrate density is equal to the water density.

When evaluating the filtration properties of drilling muds treated with reagents, the basis of the drilling fluid composition will be chalk of 50 μm dispersion. The solution forms a mud cake with an average filtration value (between the filtration values of the solutions with a dispersion of 5 and 150 μm). With this base solution, it is possible to determine the effect of reagents on the rate of formation of a low-permeable barrier and the value of filtration for both the best and the worst cases (Fig.2).

From the obtained values of the volume of the filtrate and the filtration rate of solutions with a filler content of 50 μm dispersity, treated with reagents, following conclusions can be drawn:

• the volume of the filtrate and the filtration rate of the initial solution and the solution treated with liquid glass are approximately equal. The filtration rate after the formation of a low-permeable cake decreases more intensively if liquid glass is present in the solution. Therefore, liquid glass helps to reduce the filtration capacity of the drilling fluid;

DOI: 10.31897/PMI.2019.2.172

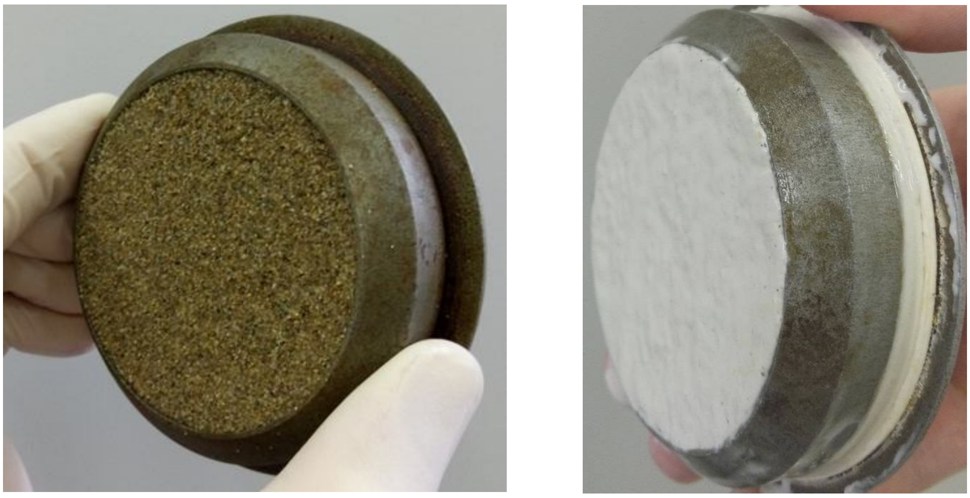

Fig.3. Sand model of rock before and after the filtration of drilling mud

• KM-PVR17 reagents and latex significantly increase the volume of mud filtrate, which adversely affects the state of the near-wellbore zone. The rock is highly water-saturated, the borehole walls are more likely to lose stability.

Let us consider the steady state filtration mode at a pressure. Since the basic drilling fluid with a dispersion of 50 μm filler forms a low-permeable barrier, the filtration rate of all drilling fluids with the content of chemical reagents evens out and will remain at the same level with time. Other things being equal (filtration areas, permeability, pressure drop), based on the Darcy filtration law, the higher the viscosity of the solution, the smaller the depth of filtrate penetration into the reservoir. In this case, the greatest influence on the moisture state of the rocks of the near-wellbore region and, as a result, on the well stability, has the rate of formation of a low permeable mud cake.

Determination of the sand model's durability properties. The purpose of this study phase is to investigate the effect of mud filtrate on the mechanical properties of the bulk model. It is established that at solution filtering through the rock, the nature of porosity and humidity changes. It is assumed that after these changes, there will be a change in the adhesion and angle of internal friction – the main parameters in the Coulomb – Mohr strength model. Depending on the change in the mechanical properties of the rock, there is a redistribution of stresses on the contour and in the marginal region around the well, changing its dimensions and the nature of its stability.

After the filtration of drilling fluids through the sand model is completed, the sample is carefully removed from the filter press (Fig.3). Next, the sample is placed in the Direct Shearand Vane Tests single-plane cut-off device, where pressure and shear are applied to it. The sample is destroyed under the stress of 102.6; 203.3; 304.0 kPa with a shear rate of 2 mm/min (Table 3). The definition of τ must be carried out with at least three different values of σ. Therefore, using the filter press and the same drilling fluid, two more rock samples are prepared.

Table 3

The results of the sand model shear test of 20 % humidity

Test	A	B	C
Applied normal stress	102.6 kPa	203.3 kPa	304.0 kPa
Peak durability	77.0 kPa	141.4 kPa	182.2 kPa
Horizontal displacement	2.674 mm	3.729 mm	4.954 mm
Shear rate		2.00 mm/min	
Final sample height	20.10 mm	19.78 mm	19.73 mm
Total displacement	3.525 mm	4.900 mm	6.100 mm

DOI: 10.31897/PMI.2019.2.172

The mechanical properties of the models through which the drilling mud was filtered are listed in Table 4.

Adhesion values range from 13.97 to 27.43 kPa. The angle of internal friction will vary in the range from 26.34 to 33.56 degrees.

The calculation of the stress-strain state of the wellbore. Based on the test results of a single-plane cut-off (Table 4), stresses on the wellbore wall and safety factor were calculated [1-3, 7, 10, 12-14].

Table 4

Test results for single-plane cut-off

Original sand model of 20 % humidity	Adhesion, kPa	Angle of internal friction, degrees
	27.3	27.58
5 μm	21.57	26.34
50 μm	16.16	30.04
100 μm	17.29	27.83
150 μm	16.42	30.85
50 μm + 3 % liquid glass	13.97	33.56
50 μm + 3 % latex	24.16	27.28
50 μm + 3 % KM-PVR17	17.59	30.03

Calculation conditions: depth h = 2000 m; drilling mud density 1200 kg/m^3; overlying rock density 2500 kg/m^3; well radius 0.2159 m; zenith angle change in increments of 15 degrees.

Let us give an example of calculation for a rock model without the influence of drilling mud filtrate (sand humidity 20%).

Ultimate strength of tangential rock stress:

$$[\tau] = k - \sigma_n \mathrm{tg}\rho = 27.43\ 10^{-3} + 40.7 \cdot \mathrm{tg}27.58 = 21.29\ \text{MPa},$$

where σ_n – normal stress on the surface, MPa; k – rock adhesion value, MPa; ρ – internal rock friction angle, degrees.

Based on the calculated values, a graph of the difference T (φ, α) of tensile strength [τ] and tangent stresses τ (Fig.4) depending on the polar angle φ on the contour of the well and the zenith angle α is built.

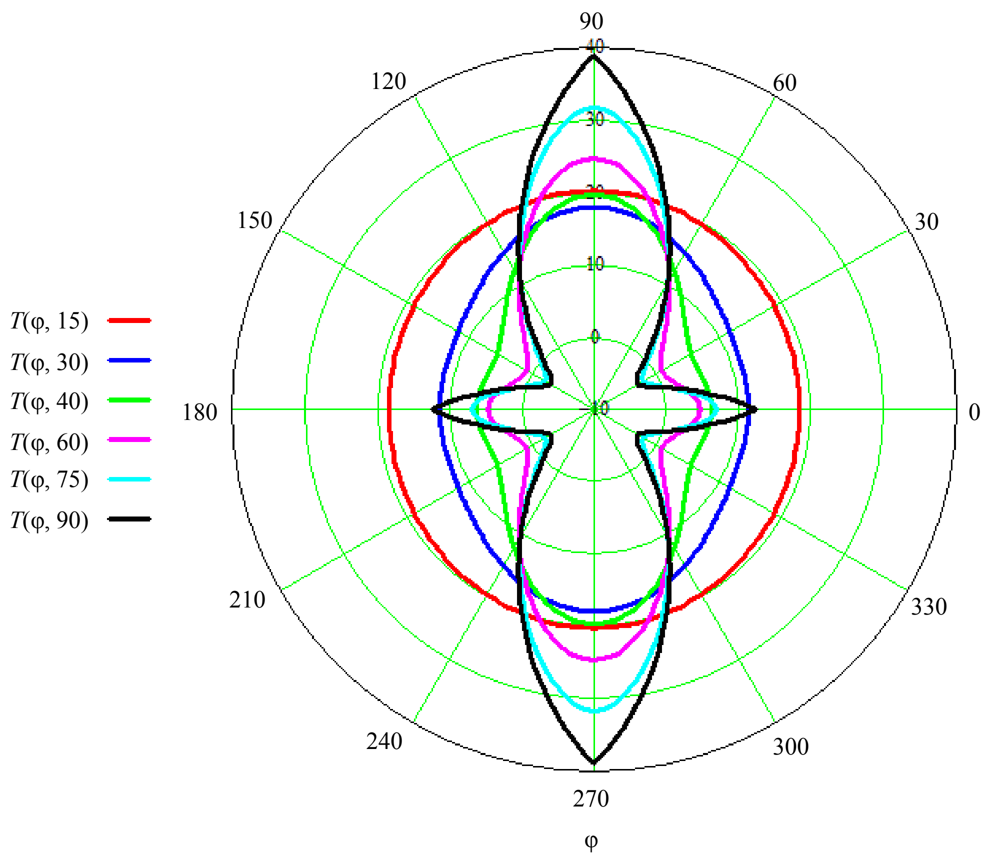

Fig.4. Difference of ultimate strength and tangential stresses on the borehole wall for a 20 % humidity sand model; φ – polar angle; 15, 30, 45, 60, 75, 90 – zenith angle of the well; horizontal cross-section of the well, view from above

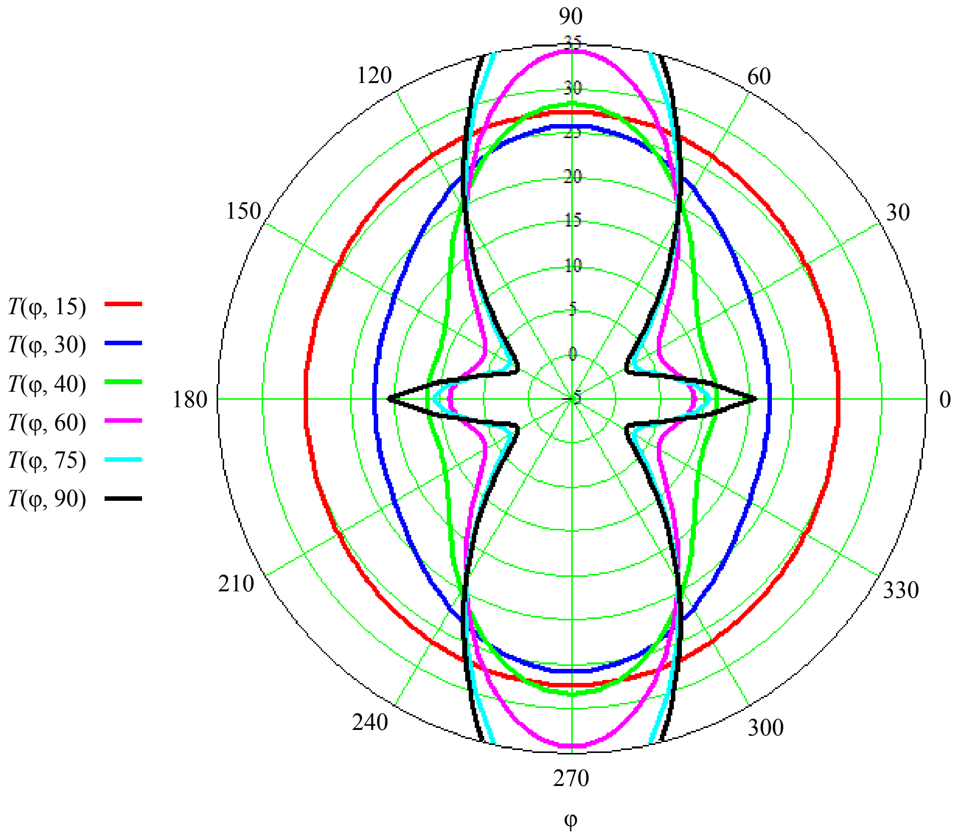

Fig.5. Difference in ultimate strength and tangential stresses on the borehole wall for the sand model after filtering 3% liquid glass solution; φ – polar angle; 15, 30, 45, 60, 75, 90 – zenith angle of the well; horizontal cross-section of the well, view from above

The area of lines, which goes beyond the boundaries of 0 MPa is the zone of destruction. As can be seen in Fig.4, the well, under the given conditions, will lose stability at the zenith angle 75 and 90°.

When analyzing the graph (Fig. 5) of the stress state of the borehole wall, calculated from the parameters of the model through which the drilling fluid was filtered with a 3 % content of liquid glass, it can be seen that, under these conditions, there are no stability loss zones (lines do not cross the zero mark). Therefore, it can be said that liquid glass helps to strengthen the borehole wall.

Conclusion. On the basis of an empirical and analytical approach to solving the problem of the rock pressure manifestation in directed well, it can be concluded that it is necessary to take into account the effect of the drilling mud on the stability of the wellbore. Both the dispersion of the drilling fluid and its chemical interaction with rocks should be considered. Currently, there are thousands of chemicals on the oil and gas market for treating drilling mud, and more than ten different components can be included in the formulation. All this limits the application of the technique to the conditions of a separate object or a geological region. Further studies in this area should be carried out to identify the general laws of drilling fluid properties influence on the ultimate state of rocks in the near-wellbore zone.

REFERENCES

1. Blinov P.A., Kulemin M.S., Arslanova E.R. Methods for assessing the fastening properties of drilling fluids for drilling loosely-coupled rocks. Burenie v oslozhnennykh usloviyakh: Materialy Mezhdunarodnoi nauchno-prakticheskoi konferentsii. St. Petersburg: «Lema», 2016, p. 11-13 (in Russian).

2. Blinov P.A., Arslanova E.R. Development of the technique for determining the stability of the directed wellbore shaft. Burenie skvazhin v oslozhnennykh usloviyakh. II Mezhdunarodnaya nauchno-prakticheskaya konferentsiya. Sankt-Peterburgskii gornyi universitet. St. Petersburg, 2017, p. 9-10 (in Russian).

3. Blinov P.A., Dvoinikov M.V., Kulemin M.S., Arslanova E.R. The effect of mud filtrate on the stress distribution in the near-wellbore zone of the well. *Estestvennye i tekhnicheskie nauki*. 2017. N 4 (106), p. 63-66 (in Russian).

4. Voitenko B.C. Applied Geomechanics in Drilling. Moscow: Nedra, 1990, p. 252 (in Russian).
5. Voitenko B.C. Management of rock pressure at drilling. Moscow: Nedra, 1985, p. 181 (in Russian).
6. Dvoinikov M.V. Well trajectory design for efficient drilling with rotary-driven systems. *Zapiski Gornogo instituta*. 2018. Vol. 231, p. 254-262. DOI: 10.25515/PMI.2018.3.254 (in Russian).
7. Karev V.I., Kovalenko Yu.F., Kulinich Yu.V. Determination of deformation and durability properties of rocks in relation to Bazhen deposits. *Tekhnologii TEK*. 2005. N 3(22), p. 17-21 (in Russian).
8. Kireev A.M. Management features of the rock pressure manifestations during the creation and the intensification of the influx in difficult geological conditions. *Byulleten' BGA*. 2001. N 1 (5), p. 15-19 (in Russian).
9. Kireev A.M Development and research of technologies and technical means of rock pressure control during well construction: Avtoref. dis… kand. tekhn. nauk. TyumGNGU. Tyumen', 2002, p. 24 (in Russian).
10. Klimov D., Karev V., Kovalenko Yu., Ustinov K. Mathematical and physical modeling of rock destruciton during making of directional wells. *Tekhnologii toplivno-energeticheskogo kompleksa*. 2006. N 5, p. 22-27 (in Russian).
11. Dvoinikov M.V., Kolev Zh.M., Vodorezov D.D., Oshibkov A.V. Model of multi-well operation with various types of bottomhole design in stationary mode. *Neftyanoe khozyaistvo*. 2014. N 11, p. 130-133 (in Russian).
12. Nikolaev N.I., Leusheva E.L. Improving the efficiency of hard rocks drilling. *Neftyanoe khozyaistvo*. 2016. N 3, p. 68-71 (in Russian).
13. Kharlamov K.N., Kovalenko Yu.F., Karev V.I., Usachev E.A. On the need to take into account the durability characteristics of rocks in determining the optimal spatial position of the well. *Burenie i neft'*. 2008. N 10, p. 18-21 (in Russian).
14. Klimov D.M., Karev V.I., Kovalenko Yu.F., Ustinov K.B. On the stability of inclined and horizontal oil and gas wells. Aktual'nye problemy mekhaniki. Mekhanika deformiruemogo tverdogo tela. Moscow: Nauka, 2009, p. 455-469 (in Russian).
15. Oshibkov A.V., Vodorezov D.D., Syzrantseva K.V., Frolov S.A., Dvoinikov M.V., Svetashov V.N., Bakirov D.L. Assessment of the stress-strain state of the joint connection construction of a multilateral wellbore. *Neftyanoe khozyaistvo*. 2015. N 6, p. 83-85 (in Russian).
16. Blinov P.A., Podoliak A.V. The method of determining the effects of drilling fluid on the stability of loose rocks. *International Journal of Applied Engineering Research*. 2016. Vol. 11, Iss. 9, p. 6627-6629.
17. Blinov P.A., Dvoynikov M.V. The process of hardening loose rock by Mud Filtrat. *International Journal of Applied Engineering Research*. 2016. Vol. 11. Iss. 9, p. 6630-6632.
18. Moradi S.S.T., Nikolaev N.I., Chudinova I.V., Martel A.S. Geomechanical study of well stability in high-pressure, high-temperature conditions. *Geomechanics and Engineering* Vol. 16(3). Iss. 3, p. 331-339.
19. Blinov P.A., Dvoynikov M.V., Sergeevich K.M., Rustamovna A.E. Influence of mud filtrate on the stress distribution in the row zone of the well. *International Journal of Applied Engineering Research*. 2017. Vol. 12. Iss. 15, p. 5214-5217.
20. Moradi S.S.T., Nikolaev N.I., Leusheva E.L. Improvement of cement properties using a single multi-functional polymer. *International Journal of Engineering, Transactions A: Basics*. 2018. Vol. 31. Iss. 1, p. 181-187.

Author **Pavel A. Blinov,** *Candidate of Engineering Sciences*, *Associate Professor*, *Blinov_PA@pers.spmi.ru* (*Saint-Petersburg Mining University*, *Saint-Petersburg*, *Russia*).

The paper was received on 29 December, *2018*.
The paper was accepted for publication on 27 February, *2019*.