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ANALYSIS OF THE DEEP DRILLING TECHNOLOGY IN UNSTABLE FORMATIONS AT THE SEMYRENKY GAS CONDENSATE FIELD

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Abstract

The paper presents a general overview of deep drilling in unstable formations at the Semyrenky gas condensate field of the Dnipro-Donetsk Trough, including well design, bottom hole assemblies (BHA), drilling conditions, and drilling muds. Problems encountered during drilling for production casing of Wells 72- and 75-Semyrenky using high-speed drilling methods are analyzed. The relationships between the rate of penetration and disturbed rock stability, volume excess and depth, as well as consistent empirical patterns in changes in mud properties and depth are established. With these technical and economic performance indicators for well drilling are given, elements of a borehole stability management strategy were defined, the principles of mud selection for drilling through problem zones are validated. The paper discusses the requirements to a mud hydraulics program to reduce the erosion of borehole walls, specific borehole preparation techniques, such as reaming and gauging, for drilling in problem zones, and alternative options to ensure borehole stability.

Keywords:
Borehole stability;
Statistical models;
Hole gauging;
Hole geometry;
Drilling mud;
BHA.

1. Introduction

The geological conditions for drilling deep gas and gas condensate wells at the fields of the Dnipro-Donetsk Trough (DDT) are quite complicated, with rocks tending to lose stability. This affects well quality (borehole profile and caverns) and technical/economic performance indicators for well design. Frequent cavings-in and collapses limit drilling speeds and increase the cost of wells and therefore the cost of natural gas production.

In this connection, it is necessary to note the dependence of the drilling conditions and associated problems caused by the loss of stability of the wellbore walls in various oil and gas provinces of the world [1-6].

The purpose of this paper is to analyze and summarize the operating experience of contractors drilling deep Wells 72 and 75 at the Semyrenky gas condensate field under borehole instability conditions and their cooperation with scientific institutions to address some engineering issues related to rock stability prediction and drilling the existing wells to completion.

According to the approved tectonic zoning plan, the Semyrenky field is located within the near-axial zone in the central part of DDT. Administratively, the field is located on the territory of Shyshatsky and Myrgorod Districts in Poltava Region, 25 km northeast of the city of Myrgorod (fig.1).

The field was discovered by the state-owned Poltavanaftogazgeologiya company in 1990. The field has been under exploration since 1974. At present, exploration wells are being drilled by PJSC Naftogazvydobuvannya, a private joint stock company.

The field's geology includes Carboniferous, Permian, Triassic, Jurassic, Cretaceous, and Cenozoic deposits. The most recent wells have penetrated Lower Carboniferous deposits; lithologically, these deposits are alternating sandstone, mudstone, and siltstone, with rare limestone interlayers. In Lower Carboniferous deposits (marker horizons $v_{B_2}^{2-2}, v_{B_2}^{2-1}, v_{B_2}^{1}$), the same-name structure is interpreted as a brachyanticline, which is extended to the northwest and gradually flattens upsection; in Mesozoic deposits, it is represented as a terrace.

In terms of geological oil and gas zonation, the Semyrenky field belongs to the Glinsko-Solokhovsky oil and gas region with 13 commercial gas condensate reservoirs in Upper Visean deposits (Horizons B-16, B-17, B-18, and B-19). Some of these reservoirs are under commercial production and others are not; hydrocarbon reserves for the latter are classified as prospected reserves.

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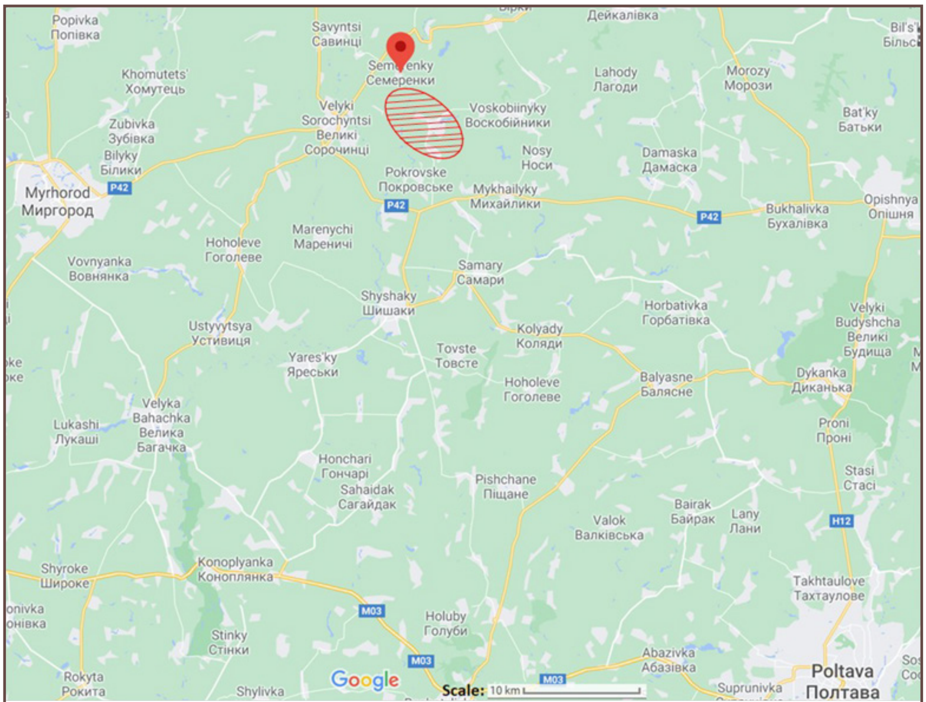

Fig.1. Overview map of the area of the Semyrenky gas condensate field

2. Drilling techniques

Table 1 shows target and actual designs of Wells 72- and 75- Semyrenky. Casing depths are slightly different, due to the requirement to achieve drilling goals, namely: to confirm reservoir characteristics and recovery mechanisms, identify and update the boundaries of productive pools, and estimate hydrocarbon reserves in specific reservoir areas of Horizons B-17-18-19 within the pool outline. Well 72 is a vertical well and Well 75 is a directional well with a 352 m outstep (195° azimuth, 5330 m depth in Horizon B-17 top).

During drilling for surface casing in Well 72-Semyrenky, a 444.5 mm three-cone drill bit was used rotated by the top drive, along with fresh water clay mud with a weight of 1130 kg/m^3. For intermediate casing drilling, 311.1 mm PDC bits were used rotated by the top drive, along with polymer low-solids content mud with a weight of 1160–1180 kg/m^3.

For host casing drilling, 219.1 mm PDC bits were used, along with non-dispersing polymer drilling mud [7] with a weight of 1120–1340 kg/m^3, by a combined (top drive and PDM) method. During drilling for liner casing, 152.4 mm PDC bits were used for the combined method, along with WITER II invert emulsion mud [7] with a weight of 1240–1260 kg/m^3.

For surface casing drilling in Well 75-Semyrenky, a 444.5 mm PDC bit was used rotated by the top drive, along with fresh water clay mud with a weight of 1100 kg/m^3. For intermediate casing drilling, 311.1 mm PDC bits were used rotated by the top drive, along with polymer low-solids content mud with a weight of 1140–1210 kg/m^3.

For host casing drilling, 219.1 mm PDC bits were used for the combined method, along with non-dispersing polymer drilling mud with a weight of 1220–1360 kg/m^3.

Table 2 shows the information about the drilling practices on Wells 72- and 75-Semyrenky.

Table 3 shows the information about BHA

Table 1

Well designs

Target design		Actual design	
String	**Depth, m**	**String**	**Depth, m**
72-Semyrenky			
339.7 mm surface casing	300	339.7 mm surface casing	307
244.5 mm intermediate casing	2760	244.5 mm intermediate casing	2773
177.8 mm host casing	5020	177.8 mm host casing	5180
127 mm liner casing	4820–5470	127 mm liner casing	5140–5420
75-Semyrenky			
339.7 mm surface casing	300	339.7 mm surface casing	299
244.5 mm intermediate casing	2760/2810	244.5 mm intermediate casing	2773/2823
177.8 mm host casing	5020/5070	177.8 mm host casing	5179/5229
127 mm liner casing	4820–5470 / 4870–5520	127 mm liner casing	5132–5420 / 5199–5470

Note. For Well 75, the numerator is true vertical depth and the denominator is measured depth.

Table 2

Drilling practices

Options	339.7 mm surface casing	244.5 mm intermediate casing	177.8 mm host casing	127 mm liner casing
Well 72-Semyrenky				
System	Top drive	Top drive	Top drive+PDM	Top drive+PDM
Bit weight, kN	60	from 10-50 to 60-130	from 20-50 to 30-90	from 20-50 to 30-100
Bit rotations per minute	40-60	from 55-75 to 105-110	40+161	60+161
Drilling pumps productivity, l/s	50-60	from 38-45 to 48-49	32-34	12.0-12.5
Standpipe pressure, MPa	2-4	from 3.5-7.0 to 14.4-17.3	from 15.8-19.5 to 19.2-22.3	from 15.8-19.5 to 19.2-25.0
Well 75-Semyrenky				
System	Top drive	Top drive	Top drive+PDM	Top drive+PDM
Bit weight, kN	10-80	from 5-100 to 20-130	from 30-80 to 80-120	50-90
Bit rotations per minute	30-60	from 45-120 to 118-131	from 40-50 to 141-196	39-42+121
Drilling pumps productivity, l/s	10-59	from 39.0-44.5 to 49-51	28-35	10.5-11.5
Standpipe pressure, MPa	0.5-6.0	from 11.0-14.6 to 12.1-17.3	from 11.8-22.1 to 22.3-25.0	24.5-26.2

for drilling various intervals in Wells 72- and 75-Semyrenky. Based on the analysis of BHA used for deep drilling at the Semyrenky field [8], BHA static performance is shown as satisfactory in terms of deviation prevention, for the conditions when there are no local caverns. It was pointed out [8] that in some cases these BHA are dynamically unstable, i.e. their use leads to higher lateral vibration of the bottom hole assembly from the drill bit. This has a negative impact on bit performance.

BHA selected for production casing drilling are suited for difficult drilling conditions and include a HYDRA-JAR 6½″ hydraulic jar and ShMU-178 junk baskets integrated at certain intervals. Schlumberger's PowerDrive rotary steerable system with the TeleScope telemetry service was used for directional drilling.

3. Analysis of problems

In most cases, problems related to borehole instability occurred during production casing drilling. Stratigraphically, these deposits are associated with the Middle (C_2) and Lower (C_1) Carboniferous as follows: Well 72, Moscovian (2774–3294 m), Bashkirian (3294–3915 m), Upper Serpukhovian (3915–4340 m), and Lower Serpukhovian (4340–4700 m); Well 75, Moscovian (2758–3332 m), Bashkirian (3332–3969 m), Serpukhovian (3969–4382 m), and Lower Serpukhovian (4382–4705 м). Lithologically, the problem section contains alternating mudstone, shale, siltstone, sandstone, and limestone. Formation water is classified as calcium chloride water, with salinity of 120–180 mg-eq/l.

For production casing drilling in Wells 72 and 75, non-dispersing polymer drilling mud was used with the following properties: Well 72 – weight, ρ = 1140-1330 kg/m^3; funnel viscosity, FV = 24–88 s; fluid loss, Φ = 4–7 cm^3/30 min; gel strength, $\theta_{10/10}$ = 1.0–6.7/2.–14.3 Pa; pH value 9.0–12.6; total solids, c = 8–18%; yield point, τ_0 = 0.5–4.5 Pa; consistency index, k = 0.047–1.159 Pa·s^n; nonlinearity, n = 0.489–0.864; Well 75 – ρ = 1230–1360 kg/m^3, FV = 32–97 s, Φ = 4–11 cm^3/30 min, $\theta_{10/10}$ = 1.0–9.1/4.3–16.3 Pa, pH 8.51–11.00, c = 15–22%, τ_0 = 0.44–6.10 Pa, k = 0.059–0.862 Pa·s^n, n = 0.536–0.859.

For mud rheology control, an OFITE 800 rotational viscometer was used in a laboratory environment. Data were batch processed using the method described in [9] in a class of rheologically steady state models (Bingham, Ostwald, Herschel – Bulkley, and Schulman – Casson). The Herschel – Bulkley model is the most suitable rheological model for drilling muds.

Correlation analysis methods were used to identify consistent empirical patterns in changes in mud properties with depth when drilling through problem intervals (for the results, see table 4) [10].

Statistical hypotheses H_0: ρ_{xz} = 0 with confidence probability were tested using:

$$T = \frac{\left| r_{xz}\sqrt{n} \right|}{1 - r_{xz}^2} < u_{\alpha/2} \qquad (1)$$

where r_{xz}, ρ_{xz} is the empirical estimate of the correlation ratio and its true value; n is the size of the sample of observations; $u_{\alpha/2}$ is the quantile of the standardized normal distribution.

Statistically significant correlation ratios with confidence probability α = 0.05 ($u_{\alpha/2}$ = 1.96), for which condition (1) is violated, are shaded gray in table 4. Changes in mud weight, fluid loss parameters, and pH are due to the measures to prevent the occurrence of drilling problems. Typical changes in funnel viscosity, gel strength (in particular, for 10 minutes), total solids, consistency index, and nonlinearity can be largely

Table 3

Bottom hole assembly

Drilling interval, m	BHA
Well 72-Semyrenky	
0–307	444.5SB115C; 254 mm sub, 0.56 m; 229 mm drill collar (DC), 9.25 m; 444.5 mm spiral blade stabilizer (SBS), 1.97 m; 229 mm DC, 9.3 m; 444.5 mm SBS, 1.67 m; 229 mm DC, 18.75 m; 203 mm sub, 0.4 m; 203 mm DC, 55.95 m; 203 mm sub, 0.43 m; 165 mm heavyweight drill pipe (HWDP), 28.13 m
307–2185	311.1ViS516; 203 mm sub, 0.95 m; 203 mm DC, 9.3 m; 309 mm SBS, 1.48 m; 203 mm DC, 9.43 m; 309 mm SBS, 1.48 m; 203 mm DC, 55.95 m; 203 mm jar, 10.12 m; 203 mm DC, 18.56 m; 203 mm sub, 1.14 m; 165 mm HWDP, 112.5 m
2185–2775	311.1Z519; 203 mm sub, 0.95 m; 305 mm SBS, 1.93 m; 203 mm DC, 9.42 m; 305 mm SBS, 1.93 m; 203 mm DC, 9.35 m; 305 mm SBS, 2.41 m; 203 mm DC, 55.6 m; V-stab 308, 2.34 m; 203 mm DC, 28 m; 203 mm jar, 10.12 m; 203 mm DC, 18.3 m; 203 mm sub, 1.14 m; 165 mm HWDP, 112.5 m
2786–4730	219.1XS616; PDM 172 HEMIDRILL, 8.42 m; 215.9 mm SBS, 1.59 m; 165 mm DC, 9.3 m; 215.9 mm SBS, 1.51 m; 165 mm DC, 94.49 m; 165 mm sub, 0.35 m; 165 mm jar, 9.68 m; 168 mm sub, 1.13 m; 165 mm DC, 28.4 m; 165 mm sub, 0.35 m; 127 mm HWDP, 84.37 m
4730–5180	219.1XS716; 165 mm sub, 0.36 m; 165 mm DC, 9.46 m; 165 mm sub, 0.35 m; 214.9 mm SBS, 1.59 m; 165 mm DC, 9.3 m; 215.3 mm SBS, 1.51 m; 165 mm DC, 94.49 m; 165 mm sub, 0.35 m; 165 mm jar, 9.68 m; 168 mm sub, 1.13 m; 165 mm DC, 28.4 m; 165 mm sub, 0.35 m; 127 mm HWDP, 84.37 m
5180–5208	152.4XZ516; 120 mm sub, 0.4 m; 121 mm DC, 9.38 m; 152.4 mm SBS, 1.67 m; 121 mm DC, 141.44 m; 121 mm jar, 8.84 m; 121 mm DC, 28.04 m; 121 mm HWDP, 168.96 m
5216–5372	152.4XZ516; PDM 127 HEMIDRILL, 7.58 m; 152.4 mm SBS, 1.67 m; 121 mm DC, 9.23 m; 152.4 mm SBS, 1.67 m; 121 mm DC, 150.82 m; 121 mm jar, 8.84 m; 121 mm DC, 28.04 m; 121 mm HWDP, 168.96 m
5372–5420	152.4Z613; PDM 127 HEMIDRILL, 7.58 m; 152.4 mm SBS, 1.67 m; 121 mm DC, 9.23 m; 152.4 mm SBS, 1.67 m; 121 mm DC, 150.82 m; 121 mm jar, 8.84 m; 121 mm DC, 28.04 m; 121 mm HWDP, 168.96 m
Well 75-Semyrenky	
0–300	444.5SB115C; 254 mm sub, 0.55 m; 229 mm DC, 9.41 m; 444.5 mm SBS, 2.15 m; 229 mm DC, 9.37 m; 444.5 mm SBS, 1.98 m; 229 mm DC, 18.67 m; 229 mm sub, 0.4 m; 203 mm DC, 56.1 m; 195 mm sub, 1.14 m; 165 mm HWDP, 56.24 m
300–1200	311.1XS516; 203 mm sub, 0.62 m; 308 mm SBS, 1.94 m; 203 mm DC, 9.3 m; 308 mm SBS, 1.94 m; 203 mm DC, 65.4 m; V-stab 308, 2.35 m; 203 mm DC, 27.72 m; 203 mm jar, 10.12 m; 203 mm DC, 18.77 m; 195 mm sub, 1.14 m; 165 mm HWDP, 112.51 m
1200–2825	311.1XS516; PD900 308 mm Stabilized CC (Schlumberger), 4.16 m; SRX Slick (Schlumberger) 308 mm, 2.42 m; NM DC-210 (Schlumberger), 8.02 m; 203 mm DC, 74.89 m; 203 mm jar, 10.12 m; 203 mm DC, 55.64 m; 195 mm sub, 1.14 m; 165 mm HWDP, 112.51 m
2904–4557	219.1XS616; PDM 172 HEMIDRILL, 8.4 m; 215.9 mm SBS, 1.77 m; 165 mm DC, 9.38 m; 215.9 mm SBS, 1.51 m; 165 mm DC, 94.37 m; 165 mm sub, 0.36 m; 165 mm jar, 9.67 m; 168 mm sub, 1.03 m; 165 mm DC, 28.24 m; 165 mm sub, 0.35 m; 127 mm HWDP, 84.34 m.
4557–4621	219.1XS616+219.1XS716; 165 mm sub, 0.36 m; 165 mm DC, 9.35 m; 215.9 mm SBS, 1.5 m; 165 mm DC, 9.38 m; 215.9 mm SBS, 1.51 m; 165 mm DC, 94.37 m; 165 mm sub, 1.03 m; 165 mm jar, 9.67 m; 168 mm sub, 1.03 m; 165 mm DC, 28.24 m; 165 mm sub, 0.35 m; 127 mm HWDP, 84.34 m
4621–4915	219.1XS716; PDM 172 HEMIDRILL, 8.4 m; 215.9 mm SBS, 1.77 m; 165 mm DC, 9.38 m; 215.9 mm SBS, 1.51 m; 165 mm DC, 94.37 m; 165 mm sub, 0.36 m; 165 mm jar, 9.68 m; 168 mm sub, 1.03 m; 165 mm DC, 28.24 m; 165 mm sub, 0.35 m; 127 mm HWDP, 84.34 m
4915–5151	219.1XS716; 165 mm sub, 0.36 m; 165 mm DC, 9.35 m; 215.9 mm SBS, 1.5 m; 165 mm DC, 9.38 m; 215.9 mm SBS, 1.51 m; 165 mm DC, 28.24 m; 165 mm sub, 0.35 m; 127 mm HWDP, 84.34 m
5151–5229	219.1XS616; 165 mm sub, 0.36 m; 165 mm DC, 9.35 m; 165 mm sub, 0.36 m; 215.9 mm SBS, 1.6 m; 165 mm DC, 9.38 m; 214.3 mm SBS, 1.51 m; 165 mm DC, 94.37 m; 165 mm sub, 0.36 m; 165 mm jar, 8.58 m; 168 mm sub, 1.03 m; 165 mm DC, 28.24 m; 165 mm sub, 0.35 m; 127 mm HWDP, 84.34 m
5231–5470	152.4XZ516+152.4R613; PDM 127 HEMIDRILL, 7.53 m; 152 mm SBS, 1.68 m; 121 mm DC, 9.46 m; 152 mm SBS, 1.66 m; 121 mm DC, 179.68 m; 121 mm jar, 8.81 m; 121 mm DC, 28.33 m; 121 mm HWDP, 168.81 m

Table 4

Correlation analysis of properties of non-dispersing polymer muds

Mud parameters	Well 72-Semyrenky		Well 75-Semyrenky		Criterion T_r
	r_{xz}	T	r_{xz}	T	
Weight	0.847	14.374	0.956	60.452	2.209
Funnel viscosity	0.894	21.351	0.708	7.781	1.893
Fluid loss	-0.745	8.018	-0.064	0.353	–
$Gel_{1/10}$	0.706/0.883	6.752/19.294	0.848/0.901	16.567/26.265	1.254/0.299
pH	-0.914	26.486	-0.811	12.999	1.428
Total solids	0.937	36.645	0.868	19.281	1.315
Yield point	0.225	1.134	0.708	7.772	–
Consistency index	0.810	11.323	0.666	6.548	1.097
Nonlinearity	-0.732	7.562	-0.505	3.713	1.278

attributable to the erosion of borehole walls.

In this connection, the results of testing of a set of statistical hypotheses $H_0:\rho_{xz}^{(72)}=\rho_{xz}^{(75)}$ for mud properties for Wells 72- and 75-Semyrenky, respectively, are conclusive. Table 4 contains the estimates for tests

$$T_r=\frac{\left|\zeta^{(72)}-\zeta^{(75)}\right|}{\sqrt{\left(n^{(72)}-3\right)^{-1}+\left(n^{(75)}-3\right)^{-1}}}$$

of hypotheses H_0, where $\zeta=\frac{1}{2}\ln\left(\frac{1-r_{xz}}{1+r_{xz}}\right)$ is the Fisher transformation. The condition for acceptance of hypotheses H_0 is determined similarly to $T_r < u_{\alpha/2}$ and with confidence probability α = 0.05 (shaded gray in table 4). For mud weight, the hypothesis has been rejected.

Table 5 contains some information about the problems related to borehole instability during production casing drilling in Well 72-Semyrenky. A typical relationship is observed between the depth at which a problem occurred and the time of its occurrence after penetration: this time is reduced with depth. The time between the first and subsequent occurrences of a problem is also reduced.

The data shown in table 5 are based on the results of borehole section gage logging by Schlumberger, which were then used to estimate cavernosity and caving ratios and the hole closure rate. The caving ratio is estimated as a ratio of the actual averaged volume of drilling returns to the rated volume in each of the intervals at a measuring depth. Figure 2 compares cavernosity ratios based on the results of borehole section gage logging completed on March 6, 2019 and March 25, 2019 and shows the estimated average rates of hole closure in the interval where

Table 5

Borehole instability in Well 72-Semyrenky

First occurrence		Subsequent occurrences	
total depth, m / mud weight, kg/m³	date / time of occurrence / time after penetration, hours – min	total depth, m / mud weight, kg/m³	date / time of occurrence / time from the moment the previous problem occurred, hours – min
2975 / 1170	23.02.19 / 06:00 / 125–00	3860 / 1180	28.02.19 / 11:00 /106– 00
		4479 / 1190	04.03.19 / 21:00 /–
		4730 / 1220	12.03.19 / 05:00 /–
3065 / 1170	23.02.19 / 20:00 / 112 – 00	3860 / 1180	28.02.19 / 12:00 /86 – 00
		4479 / 1190	04.03.19 / 22:00 /–
		4730 / 1220	12.03.19 / 05:00 /–
3155 / 1180	24.02.19 / 03:00 / 107 – 00	3860 / 1180	28.02.19 / 14:00 /86 – 00
		4479 / 1190	04.03.19 / 20:00 /4 – 00
		4479 / 1190	05.03.19 / 00:00 /–
		4730 / 1220	12.03.19 / 05:00 /–
3515 / 1170	26.02.19 / 06:00 / 40 – 00	3860 / 1170	27.02.19 / 22:00 /69 – 15
		4730 / 1220	11.03.19 / 18:00 /–
3575 / 1170	26.02.19 / 08:00 / 32 – 00	3860 / 1170	27.02.19 / 16:00 /–
		4730 / 1220	11.03.19 / 18:00 /–

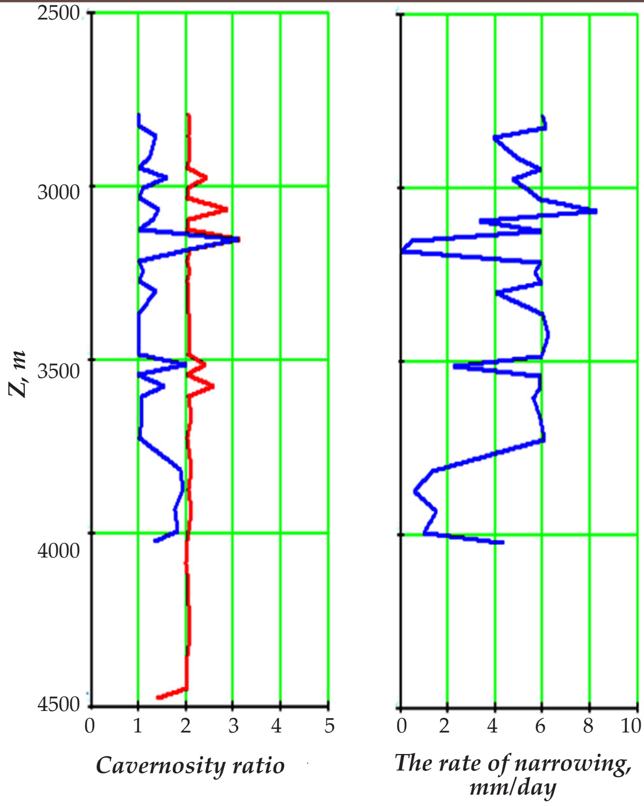

Fig.2. Caliper logs (--- of March 6, 2019 and --- of March 25, 2019) and the average rate of hole closure, Well 72- Semyrenky

Fig.4. Photo of a core sample: mudstone broken into pieces from the 4982–4990 m interval, Well 72

the problems occurred. The results of statistical processing of some data are shown in table 6.

Borehole stability was assessed subject to the following cavernosity ratios [11]:

1 – Rocks are stable;

1…3 – Rocks are temporarily stable;

> 3 – Rocks are unstable;

1...5 – Borehole is caving in;

> 5 – Borehole walls collapse.

Therefore, substantial cavings-in and collapses occurred in the interval of 2795–4445 m in the well in question, which required intervention in the drilling technology. The same data were obtained from other wells at the field, with visual evidence of a large number of cuttings and rock fragments carried up during mud circulation of drilling mud (fig.3) and unstable core recovery (fig.4).

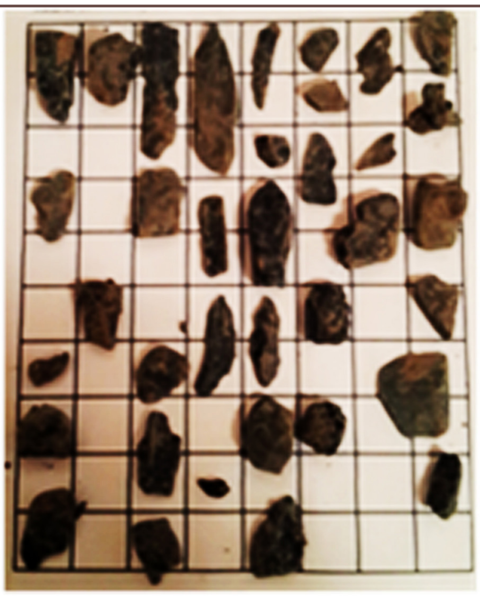

Fig.3. Photo of cuttings fallen from a depth of 3522 m, Well 75 (Scale: 2 cm in a cellule)

Despite the challenge of maintaining borehole stability through mud control, an attempt was still made to select the weight and structural/mechanical properties of a non-dispersing polymer drilling mud allowing to drill one hole through problem zones to the top of pay. For this purpose, Schlumberger software was used for geomechanical 3D modeling of the state of rock stress in unstable formations and validation of mud weight [12].

4. Factors affecting borehole stability

A mud hydraulics program, which includes hydraulics management subject to optimization criteria, functional requirements, and process limitations, plays an important role when drilling in problem zones. It should be noted that some requirements to the selection of mud pump rates are contradictory. For example, bottomhole cleaning and cuttings transport require higher mud pump rates, whereas washout prevention requires lower mud pump rates.

The analysis of field data obtained while drilling at the Semyrenky field suggests that not enough attention is paid to rock erosion when a mud hydraulics program is developed for problem intervals. Table 7 shows the estimated transport and erosive capacities

Table 6

Results of statistical processing of borehole section gage logging data

Statistical characteristics	Cavernosity ratio	Caving ratio	Hole closure rate, mm/day
Expected value	1.317	2.019	4.409
Dispersion	0.278	3.021	5.097
Interval estimate of the expected value	1.317±0.193	2.019±0.638	4.409±0.828
Correlation ratio	0.495	0.263	0.124
T criterion for testing statistical hypothesis H_0:ρ = 0	3.655	1.572	0.702

of a drilling mud for the drill collar annulus and the drill pipe annulus in Well 72. The estimates are based on the following mud rates *Q*: 36, 30, 25 and 20 l/s. Flow properties of a non-dispersing polymer drilling mud were determined using an OFITE 1100 rotational viscometer, subject to temperature conditions for the most suitable rheological model, the Herschel–Bulkley model: τ_0 = 2.40 Pa, *k* = 0.0116 Pa·s^n, *n* = 0.9085.

The cuttings transport capacity of the annular flow was estimated using the indicator [13]:

$$k_v(z) = \frac{S_0(z)}{S(z)} \qquad (2)$$

where *S(z)* is the annular flow area at a depth *z*; $S_0(z)$ is the cross sectional area of a fluid flow for which $v(z) > v_0(z)$; $v_0(z)$ is the sedimentation rate for mud particles in a fluid flow (taken equal to 0.45 m/s).

The erosive capacity of muds can be estimated from wall shear stresses $\tau_w(z)$. Greater values of $\tau_w(z)$ correspond to a higher erosive capacity of a specific mud under specific conditions.

Table 7

Estimated cuttings transport and erosive capacities of a non-dispersing polymer drilling mud

Annulus diameter, mm	*Q*, l/s	v_m, m/s	k_v	τ_w, Pa
220/165	36	2.726	0.947	6.386
220/165	30	2.243	0.938	5.892
220/165	25	1.846	0.928	5.467
220/165	20	1.455	0.913	5.027
220/127	36	1.683	0.933	4.382
220/127	30	1.387	0.922	4.159
220/127	25	1.144	0.909	3.965
220/127	20	0.903	0.890	3.760

In table 7, the estimates of transport capacity $k_v(z)$ and erosive capacity $\tau_w(z)$ of muds are made using laminar flow equations for non-Newtonian fluids in a concentric annulus. The estimates are made for the conditions existing in Well 72-Semyrenky (depth *z* = 2975 m). Specifically, the mud pump rate *Q* has a different impact on the rate at which the transport and erosive capacities are changing. It should be noted that wall shear stresses $\tau_w(z)$ are higher for the drill collar annulus. Reamers, centralizers, stabilizers, etc. increase the erosive capacity of muds. It should be emphasized that even for mud particles with v_0 = 0.45 m/s the transport capacity of the flow is quite high in the 127 mm drill pipe annulus at *Q* = 20–25 l/s. Table 7 also contains data on the velocity v_m of the flow core.

As a separate matter, a drilling mud should be selected on the basis of mud tests for erosion, capillary suction time, X-ray diffraction, particle size distribution, etc. In this case, image logging seems to be the most suitable product of the drilling practice in field application [14]. Image logging is based on predicting borehole stability with the help of geomechanical pressure models and offers an opportunity to analyze the downhole situation in real time using controlled parameters during various process operations, including when mud properties change. Key control parameters for mud selection include mud weight, HP/HT fluid loss, *pH*, salinity, and water phase composition.

The main requirement to mud weight ρ_s is to ensure rock stability at borehole walls, which is formalized as [15]:

$$\rho_s = \frac{1}{g}\left(grad\ p_s + \frac{[\Delta p]}{z}\right) \qquad (3)$$

where $grad\ p_s$ is the pressure gradient for rock stability at borehole walls at depth *z*; $[\Delta p]$ is a certain pressure reserve, e.g. to ensure rock stability when pulling out of hole.

The value of $grad\ p_s$ is estimated either with the help of geomechanical models, including 3D models, or from field data. Below, the formula of Ishchenko and Selvashchuk is used for a 1D model [16]. It should be noted that in this case there is a problem of uncertainty or risk due to the reliability of data on physical and mechanical properties of rocks and conditions under which problems occur.

Mud weights were estimated for drilling through problem intervals, using field data and subject to data uncertainty. The yield point was estimated from laboratory tests carried out by UkrNIIgaz [16], subject to formation temperatures. Two typical groups of relationships between yield point σ_{ys} and depth z were identified from the findings: for 2300–2600 and 3000–5400 m depths (fig. 5).

The statistical analysis points to a correlation relationship between these two groups ($r_{\sigma z}$ = 0.458, *T* = 2.529 > $u_{0.025}$ = 1.96) and no such relationship for

3000–5400 m depths ($r_{\sigma z}$ = -0.381, T = 1.41 < $u_{0.025}$ = 1.96). The results of statistical evaluation are as follows: regression equation is σ_{ys} = 9.444 + 2.335·10^{-3}z (for 2300–5400 m depths); σ_{ys} = 20.4±2.924 MPa, S_{σ}^{2} = 16.711 MPa² (for 3000–5400 m depths).

Given initial data uncertainty, mud weights were estimated with the help of (3) as a fuzzy set $\rho_s = \{\rho, \mu_s(\rho)\}$, where $\mu_s(\rho)$ is the membership function that defines how each value of $\rho \in R^+$ is mapped to a number of $\mu_s(\rho)$ from the segment [0,1], which describes the degree of problem prevention at a given value of ρ. The membership function is estimated using the statistical simulation method for uncertain variables of rock density with the average value of ρ_r=1955 kg/m³, root-mean-square deviation of 20 kg/m³, and pressure reserve of [Δp] = 1.2–1.5 MPa for depth z = 2795 m and with the average density of ρ_r = 2010 kg/m³, deviation of 25 kg/m³, and pressure reserve [Δp] = 1.5–1.9 MPa for depth z = 3575 m. The yield point was simulated as a normal variable for 2795 and 3575 m depths (Well 72). The number of statistical experiments was 1000. The results of the simulation are shown in figure 6.

So, based on the estimated membership function $\mu_s(\rho)$ and field data, a drilling mud with a weight of 1150–1200 kg/m³ can be recommended for well drilling from a depth of 2795 m (in this case, the risk of problems is assessed as 28–50%) and a drilling mud with a weight of 1350–1400 kg/m³ can be recommended for well drilling from a depth of 3575 m (the risk of problems is 45–70%) (fig.5).

5. Technical and economic performance indicators for drilling

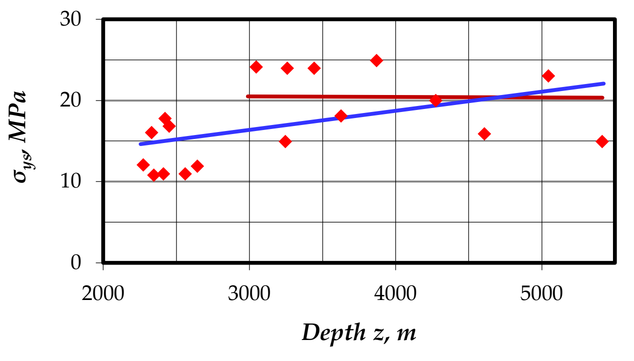

Fig.5. Yield point vs. depth (shales): 2300–5400 m; 3000–5400 m

Technical and economic performance indicators are based on the industry-approved timing classification for core, auxiliary, and service operations. Production operations such as mechanical drilling, round-trip, trip support operations, casing, and some other auxiliary and service operations are considered to be productive rig time and are included in calendar time distribution for well drilling. Actual time also includes non-productive time due to mitigation/accident response while drilling, rig crew downtime, or production operations performed beyond standard time.

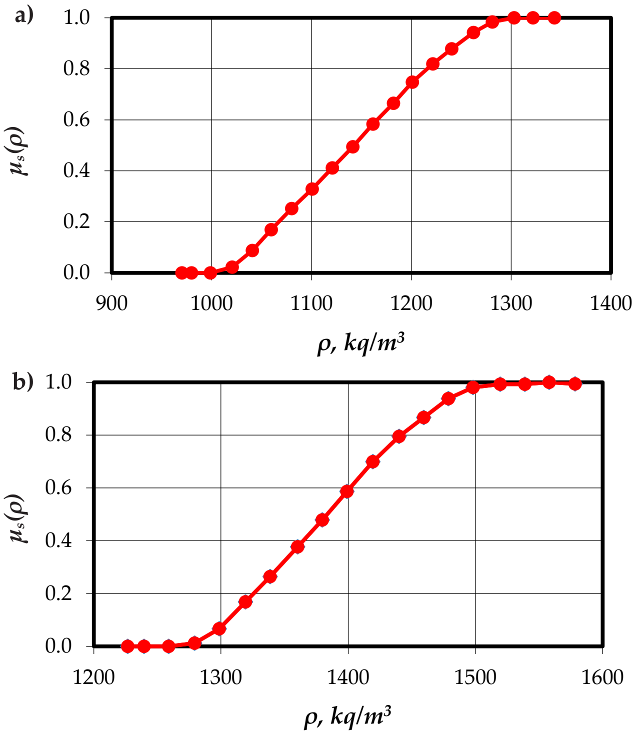

Fig.6. Membership functions for mud weight for problem prevention at depths: a) 2795 and b) 3575 m

Specific actual indicators in calendar time distribution (fig.7) make it possible to estimate the rates of penetration for relevant wells and compare them to identify process operations which can be fast-tracked through the application of appropriate process and/or organizational solutions or which, alternatively, can be planned if these production operations lead to successful mitigation response. Such operations as hole gauging, reaming, and cleaning, as well as recovery of tools stuck downhole due to caving-in, are of direct relevance to the problem under discussion and are shown in figure 7 separately from other operations. With regard to the above, drilling time vs. mitigation response time were 68 vs. 32% for Well 72-Semyrenky and 88 vs. 12% for Well 75-Semyrenky. In absolute terms, production casing drilling time was 888 h 00 min for Well 72-Semyrenky, including 281 h 45 min for mitigation response to cavings-in and collapses, and 1162 h 30 min for Well 75-Semyrenky, including 139 h 45 min for mitigation response.

Target and actual overall drilling and casing rates compare as follows: for Well 72, the target rate is 931 m/rig-month and the actual rate was 1499 m/rig-month; for Well 75, the target rate is 935 m/rig-month and the actual rate was 1148 m/rig-month.

Therefore, on the one part, drilling contractors have sped up well construction substantially; on the other part, considerable time and money are still spent for mitigation response to cavings-in and collapses and if a problem is eliminated entirely or at least mitigated, this will save relevant material resources.

There should be an interrelationship between target and actual drilling rates, i.e. both indicators

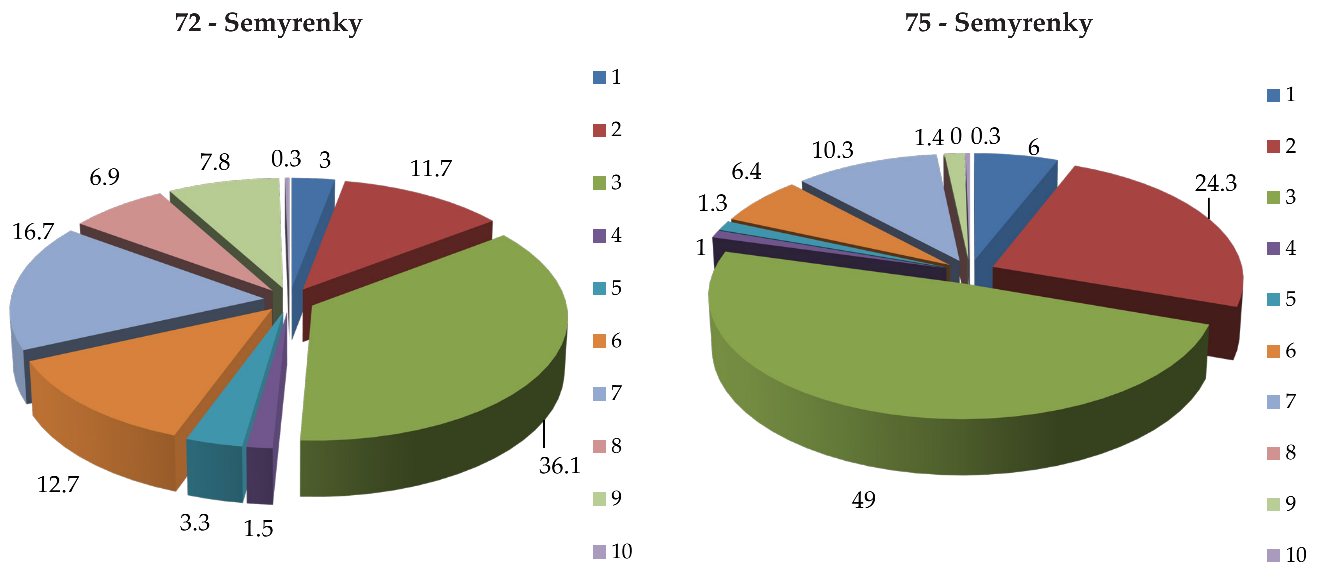

Fig.7. Percentage of time spent during production casing drilling for:
1 – BHA make up; 2 – hoisting operations; 3 – drilling; 4 – connection; 5 – gauging; 6 – other operations; 7 – reaming; 8 – gauging and reaming; 9 – hole cleaning; 10 – tool recovery using different methods

should determine each other. It means that in fact, not only should one strive to achieve the target drilling rate, but also the actual conditions of drilling operations should be taken into account when selecting the target drilling rate. Last but not least, it has to do with the geological conditions and the possibility to adjust the standard drilling time by planning mitigation response operations in case of borehole instability, such as hole gauging, etc. In this case, planning of process operations for high-quality hole cleaning should improve hole conditions, which translates into less time actually spent for mitigation response. It should be noted that in this regard, Well 72-Semyrenky and Well 75-Semyrenky are the best in terms of technical and economic performance for drilling deeper than 5000 m (see table 8) and could provide a basis for standardization of process operation times in accordance with the use of calendar time distribution for well drilling.

6. Process recommendations

A borehole stability management strategy generally includes the following [1-8,10-17]:

- identify potentially dangerous hole intervals with respect to a particular problem;
- evaluate the causes of the problem;
- develop a geomechanical model and analyze the stress-strain state in potential problem zones;
- validate well profile parameters;
- forecast pressure gradients for rock stability at borehole walls;
- select and manage well design;
- select mud type and properties;
- manage hydrodynamic conditions in the well during various process operations;
- use other prevention measures, methods and techniques.

Prevention measures should be selected according to causes of problems which may differ in similar geological conditions. Obviously, under such conditions, it is advisable to implement a package of measures that are effective for possible

Table 8

Actual drilling performance

Hole	72-Semyrenky				75-Semyrenky			
	Drilling interval, m	Net time on bottom, h	Rate of penetration, m/h	Run speed, m/h	Drilling interval, m	Net time on bottom, h	Rate of penetration, m/h	Run speed, m/h
Surface casing drilling	0–307	18.00	17.06	13.06	0–300	15.00	20.00	14.63
Intermediate casing drilling	307–2775	196.23	12.58	11.02	300–2825	113.22	22.30	12.60
Host casing drilling	2775–5180	293.00	8.21	6.69	2825–5229	487.64	4.93	3.16
Liner casing drilling	5180–5420	159.88	1.50	0.77	5229–5470	235.65	1.02	0.70

causes of problems.

The wells design at the Semyrenky field seems to indicate that in addition to drilling technology optimization, mud type selection, and mud control, the focus should be on well design validation and hole gauging/reaming techniques.

Assuming that hole gauging is essentially high-quality cleaning of the hole where cavings-in and collapses have occurred, then BHA design may be the same as the BHA design for the most recent drilling operation. With very few exceptions, there is no need to adjust BHA parameters to ensure high-quality hole cleaning. Sometimes, hole gauging may be performed during a trip, which does not only save drilling time but also is more convenient for the rig crew.

Prior to gauging, the hole is cleaned (circulated) at an increasing rotation speed. The international drilling practice [16] has proven that there are certain ranges of drill string rotation speeds at which the cuttings transport is considerably improved. These ranges correspond to rotation speeds of 100–120 and 150–180 min^{-1}.

Then drags and their respective depths are recorded when pulling out of hole. If a tight spot is encountered when pulling out of hole, the tool is lowered a little, the pump is switched to maximum rate, and the problem section is drilled up with rotation. These gauging cycles are repeated until the tool passes freely, without drill string rotation.

If a tight spot requires back reaming, reverse drilling is performed at regular rotation and cleaning conditions. If the hole conditions do not allow for back reaming in appropriate modes, back reaming is performed in stages, i.e. with intermediate stops for hole cleaning at maximum mud rates and at a recommended rotation speed. It was necessary because more cuttings or rock fragments from the walls got into the hole during reaming.

In some cases, stage-by-stage reaming was also performed when running in hole. It meant that mud circulation had to be restored at some intermediate well depths, not only at the bottom hole.

The field data suggest that reduced mitigation response time for Well 75-Semyrenky as compared to Well 72-Semyrenky could be in fact related to a somewhat lower average drilling rate (1499 vs. 1148 m/rig-month). It is known [16] that in similar conditions two strategies for well drilling in unstable formations have been developed: either to stay at the bottom hole at an optimized rate of penetration or to drill at a high rate of penetration, but with short time intervals, and then perform preventive hole cleaning and restore hole drillability by gauging and reaming.

Despite the fact that a high average rate of penetration is more important than a high instantaneous rate, there may be cases when well reconditioning operations become urgent even at lower rates of penetration. This may be due to changes in downhole conditions, the need to perform other operations, a sudden deterioration in mud quality, etc. [16]. For the best drilling technology, long intervals may be drilled over a long period of time without having to take any prevention measures.

For this reason, prevention measures such as hole gauging, reaming, and cleaning should be taken only after all drilling optimization options have already been used. It gives grounds to recommend prevention techniques which are based on optimization of performance of their operations, including parametrization of operations, formation of local optimality criteria and a system of restrictions for operation parameters, and selection of an optimality criterion and operation parameters.

BHA was generally selected subject to polyfunctional requirements that reflect its efficiency depending on a number of technical, process, and natural factors [17]. Since quite a few of these factors affecting borehole stabilization are random, BHA selection is based on a statistical decision making model.

Requirements are developed and implemented in a certain BHA class ϑ to drill relevant hole intervals, depending on hole path geometry and drilling conditions. Given data uncertainty, BHA selection corresponds to a system of restrictions which reflect the requirements to well construction conditions and are implemented as a statistical decision making model [9]:

$$\begin{cases} R\left(p^{\nu},\ a^{\nu}\right) \to min,\ \nu \in \vartheta,\ p^{\nu} \in D^{\nu}; \\ \varphi\left(p^{\nu}\right) \le 0, \end{cases} \qquad (4)$$

where $R(p^{\nu},a^{\nu})$ is the risk of the ν-th BHA from alternatives class ϑ; $p^{\nu} = (p_1^{\nu},p_2^{\nu},\ldots,p_n^{\nu})^T$ is the vector of variables for the ν-th BHA with a range of definition D^{ν}; $a^{\nu} = (a_1^{\nu},a_2^{\nu},\ldots,a_m^{\nu})^T$ is the vector of known parameters; $\varphi(p^{\nu})$ is the system of restrictions for BHA parameters.

The system defines restrictions for the drilling parameters, BHA geometry and integrity, as well as static and dynamic characteristics of BHA components. The model (4) takes into account data uncertainty for some parameters, including position of points where reamers, centralizers, stabilizers, etc. come into contact with borehole walls, zenith angle, drilling parameters, and local caverns. Class ϑ of BHA alternatives is defined by special design features, dimensions, and location of BHA components.

The risk function $R(p^{\nu},\ a^{\nu})$ reflects the probability that the conditions of the solution to problem (4) for static and dynamic BHA characteristics will be violated under data uncertainty. Risks are assessed using statistical simulation methods and the analysis of findings. Using model (4), a suggestion is made for BHA for drilling through problem intervals with minimum risks resulting from disturbed dynamic stability while drilling and reaming in problem intervals.

Based on the analysis of field data for Wells 72 and 75, a feasibility study was performed to evaluate the possibility of using the WITER II inverted emulsion drilling mud [7] for production casing drilling. For the same rates of penetration in case of drilling with a non-dispersing polymer mud and an inverted emulsion mud, operating expenses for mitigation response and hole quality improvement are estimated to be reduced by almost USD 180 thousand.

A UWD (underreaming-while-drilling) technology was also considered [3] together with the method by Voytenko [1], which are both based on the removal of rock from an unstable zone in order to reduce the hole closure rate. However, the need for several BHA designs with a different number of reamers due to varying rock hardness at the bottomhole and in the underreamed formation has eventually led to abandonment of this technology in favor of well design modifications.

An alternative design for Well 79-Semyrenky to be drilled: 473.1 mm surface casing is run to a depth of 300 m; 339.7 mm first intermediate casing, to a depth of 850 m; 244.5 mm second intermediate casing, to a depth of 3800 m; 177.8 mm host casing, to a depth of 5180 m; 114.3 mm slotted liner is set in the interval of 5080–5450 m. So, the focus is on high-speed drilling with fast penetration through unstable zones in two stages followed by their sealing by the second intermediate casing and then by the production casing.

Conclusions

1. The analysis of the drilling technology and well construction parameters for Wells 72 and 75 at the Semyrenky field suggests that the drilling contractors have acted competently, which resulted in high drilling rates and accident-free well drilling in challenging geological conditions. At the same time, there is potential for improved efficiency of deep drilling at the Semyrenky field. A significant amount of time was spent for mitigation response to borehole instability during drilling for production casing in Wells 72 and 75 (32 and 12% of calendar time distribution, respectively).

2. Borehole instability at the DDT fields is the result of a number of factors affecting the borehole in different ways, even under similar geological conditions. The analysis of field data for the existing wells, especially relationships between the rate of penetration and rock instability, cavernosity and caving ratios, and the patterns in changes in mud properties with depth suggests that mechanical and chemical erosion has a considerable impact on the occurrence of this particular problem.

3. A borehole stability management strategy is validated, which includes a package of measures ranging from problem prediction through selection of well profile and design, mud type and properties to the use of alternative techniques. An integrated approach is recommended which includes prevention of problems caused by various factors. The requirements to mud selection for drilling through problem zones are developed. Attention is drawn to the fact that it is advisable to optimize a mud hydraulics program to reduce wall erosion.

4. Specific borehole preparation techniques such as reaming and gauging are discussed and the principles for selecting process parameters for drilling in problem zones are proposed. Using a statistical decision making model, a model for efficient BHA selection is validated to meet polyfunctional requirements under data uncertainty. To reduce mitigation response expenses, a feasibility study is performed to evaluate the possibilities of using an inverted emulsion drilling mud for production casing drilling and an alternative well design with an additional intermediate casing.

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Анализ технологии бурения глубоких скважин в неустойчивых отложениях на Семиренковском газоконденсатном месторождении

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Реферат

Изложены общие сведения о бурении глубоких скважин в неустойчивых отложениях на Семиренковском газоконденсатном месторождении Днепровско-Донецкой впадины: конструкции скважин, компоновки низа бурильной колоны (КНБК), режимы бурения, буровые растворы. Проанализированы осложнения при бурении скважин 72- и 75-Семиренковская под эксплуатационные колонны с применением силовых режимов. Установлены зависимости между скоростью бурения и нарушением устойчивости пород, коэффициентов кавернозности и обвалообразования с глубиной, а также эмпирические закономерности изменения технологических свойств бурового раствора с глубиной. Приведены технико-экономические показатели бурения скважин. Сформулированы элементы стратегии управления устойчивостью стенок скважин. Обоснованы принципы выбора бурового раствора для прохождения зон осложнений. Рассмотрены требования к гидравлической программе промывки для снижения эрозии стенок скважин, особенности технологии подготовки ствола (проработка, шаблонировка) при бурении в осложненных условиях, а также альтернативные варианты для обеспечения устойчивости стенок скважин.

Ключевые слова: устойчивость стенок скважины; статистические модели; шаблонировка скважины; геометрические параметры ствола скважины; буровой раствор; КНБК.

Semirenkov qaz-kondensat yatağında qeyri-sabit çöküntülərdə dərin quyuların qazılması texnologiyasının təhlili

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Xülasə

Dneprovsk-Donetsk çökəkliyinin Semirenkov qaz-kondensat yatağının qeyri-sabit çöküntülərində dərin quyuların qazılması haqqında ümumi məlumatlar verilmişdir: quyuların konstruksiyaları, qazma kəmərinin aşağı hissəsinin komponovkası (QKAHK), qazma rejimləri, qazma məhlulları. Güc rejimlərinin tətbiqi ilə 72 - və 75-ci Semirenkovskaya quyularının istismar kəmərləri üçün qazılması zaman baş verən mürəkkəbləşmələr təhlil edilmişdir. Qazma sürəti ilə süxurların dayanıqlılığının pozulması, dərin uçqunəmələgəlmə və kavernalılıq əmsalları, həmçinin qazma məhlulunun texnoloji xassələrinin dərinliklə dəyişməsinin empirik qanunauyğunluqları arasında asılılıqlar müəyyən edilmişdir. Quyuların qazılmasının texniki-iqtisadi göstəriciləri verilmişdir. Quyu divarlarının dayanıqlığının idarəolunma strategiyasının elementləri formalaşdırılmışdır. Mürəkkəbləşmə zonalarının keçilməsi üçün qazma məhlulunun seçilməsi prinsipləri əsaslandırılmışdır. Quyu divarlarının eroziyasının azaldılması üçün hidravlik yuyulma proqramına qoyulan tələblər, mürəkkəbləşmə şəraitlərində qazma zamanı lülənin hazırlanması (işlənmə, şablonlaşdırma) texnologiyasının xüsusiyyətləri, həmçinin quyu divarlarının dayanıqlığının təmin edilməsi üçün alternativ variantlar nəzərdən keçirilmişdir.

Açar sözlər: quyu divarlarının dayanıqlılığı; statistik modellər; quyunun modelləşdirilməsi; quyunun şablonlandırılması; quyu lüləsinin geometrik parametrləri; qazma məhlulu; QKAHK.