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Technology Of Drilling Of Slant Well On The Field Of Western Siberia

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Abstract
The technology of drilling slant exploitation well in the oilfield of Western Siberia has been studied. Development of well construction has taken into account the next geological features of the section: permafrost rocks occur to the depth of 260 m, and iciness also takes place. Well construction is selected on the base of intervals of incompatible drilling conditions. The designed profile includes several intervals: one vertical interval, one zenith angle buildup section, two hold sections and one zenith angle drop section. A check calculation of the setting depth of the intermediate casing for the condition of preventing hydraulic fracturing of rocks near the shoe was carried out, and the safety factor of rocks for hydraulic fracturing was found. Drill pipes calculation includes determination of their length and diameter as well as allowable setting depth for drill pipes. This article demonstrates drilling methods, borehole under-reaming methods and the main parameters for the performance of technological operations of directional drilling. A drilling rig has been selected according to the allowable hook load. The density of the used drilling muds has been substantiated for the intervals of compatible drilling conditions, types and parameters of muds.

Keywords
directional well, drilling, borehole profile, well construction, drilling rig

Introduction

Novoportovskoe oil-gas-condensate field belongs to Western Siberian oil and gas province. During drilling in this field the next sections are distinguished (Ivanova et al., 2018; Ivanova et al., 2018; Savenok et al., 2020; Moroz et al., 2020; Baranov et al., 2017):

- Liable to drilling mud losses. This drilling trouble results in full or partial loss of drill mud circulation, which can lead to an emergency;
- Liable to caving and failure. This drilling trouble can cause considerable narrowing of a borehole. Usually, caving and failures occur in deviated intervals built with soft or unstable rocks;
- Liable to gas, water and oil shows; This phenomenon breaks the normal process of drilling, causes equipment wear and leads to emergencies;

Liable to sticking and jamming of BHA and drill string, differential sticking, packing, drilling mud thinning, etc. (Dzhus et al., 2020; Andrusyak et al., 2017; Lao et al., 2016).

Organization of the Text

Gradients of reservoir pressure grad PRES and hydrofracturing pressure grad PFR are found using the formula

$$gradP_{RES_Z} = \frac{P_{RES}}{Z}, \tag{1}$$

$$gradP_{FR_Z} = \frac{P_{FR}}{Z}, \tag{2}$$

where P_{RES}, P_{FR} – reservoir and hydrofracturing pressure on depth Z, respectively, MPa.

Development of well construction has taken into account the next geological features of the section: permafrost rocks occur in the interval of 0 - 260 m. The temperature varies from -7 to -1,5° C; iciness is in the interval of 0.15 – 0.28. Reservoir pressures along the whole section of designed wells are equal to hydrostatic pressure (Ka = 1.00). Gas horizons lie in the interval of 505 - 2035 m, and the anomaly ratio is Ka = 1.00. Oil saturated horizons occur at a depth of 1013 - 2060 m, and the anomaly ratio is Ka = 1.00. Oil exploitation target U2-6 lies in the interval of 2040 – 2060 m with reservoir pressure being P_{RES} 2040 = 205 kgf/cm^2 (Ka = 1.00).

Taking into account the data mentioned above and the experience from working in the region, the next well construction is accepted.

A conductor casing with a diameter of 426 mm is lowered to the vertical depth of 50 m to isolate unstable rocks of quaternary deposits (Saga et al., 2014; Saga, 2020). Conductor casing increases the durability of casing string for longitudinal stability in the permafrost interval and is cemented to the wellhead. In case of lowering the level behind the casing in the process of waiting-on-cement, cement slurry should be topped up (poured behind conductor casing).

The surface casing with a diameter of 324 mm is lowered to the vertical depth of 480 m (measured depth is 480 m, too) and cemented to the wellhead. Surface casing setting depth is selected with the purpose of isolating permafrost rocks. The surface casing prevents hydraulic fracturing of rocks near the shoe in case of a gas blowout from Cenomanian strata (PK_1) during drilling for the intermediate casing. Surface casing increases the durability of casing string for longitudinal stability in the permafrost interval, and prevents rocks from melting and failure. It also prevents from caving of rocks of the Oligocene and upper part of the Cretaceous systems in the process of drilling for intermediate string and provides isolation of groundwater of the Anthropogenic-Oligocene complex.

Intermediate casing with a diameter of 245 mm is lowered to the vertical depth of 1100 m (drilled depth - 1175 m) and cemented to the wellhead.

The setting depth of the intermediate casing is selected to provide isolation of upper gas horizons, which lie in the interval of 505 – 1013 m (vertical depth) and to cover unstable rocks, including the upper Yarong suite. Another purpose of intermediate casing is to provide compatibility of conditions for drilling for production casing with BOP on the wellhead (Saga et al., 2014; Kuric et al., 2022; Kuric et al., 2021). Intermediate casing increases the durability of casing string for longitudinal stability in the permafrost interval. The shoe of the casing string is installed in the interlayer of hard clays.

Production casing with a diameter of 178mm is lowered to the vertical depth of 2110 m (drilled depth is 2343 m) and cemented to the wellhead.

Production casing provides exploitation of development target, disconnects all productive horizons from each other, and protects from fluid cross-flows between beds. Production casing increases the durability of casing string for longitudinal stability in the permafrost interval (Ivanova et al., 2018; Bozek et al., 2016).

The diameter of the production casing (178 mm) provides passableness of downhole pumping equipment for exploitation of development target as well as tools and devices for well servicing and overhaul. What is more, this diameter allows drilling of sidetracks.

During well construction, the depth of running the production string should be specified based on well logging results.

Figure 1 shows a graph of overlay pressures.

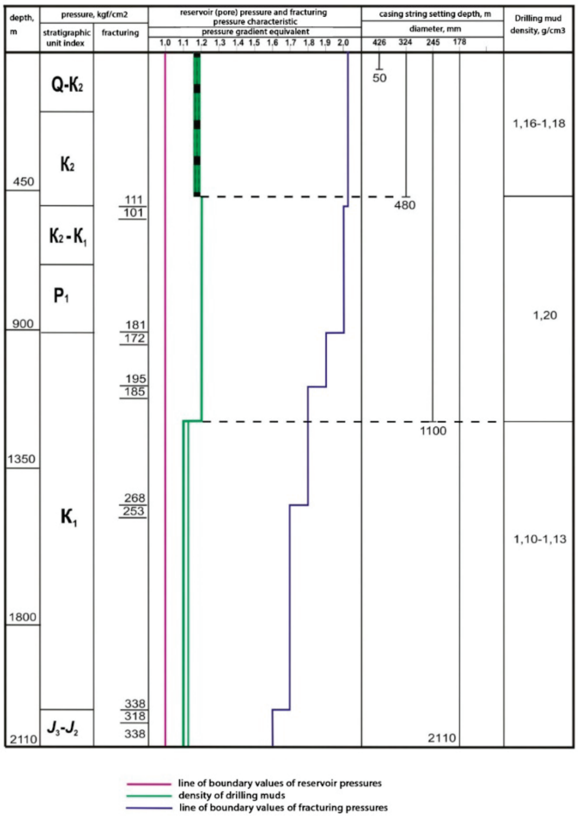

Figure 1. Graph of overlay pressures

Substantiation of well construction is shown in table 1

Table 1. Substantiation of well construction

The name of the casing string	Diameter of the casing string, mm	Setting depth (vertical), m	Purpose of casing string: substantiation of selection of diameter, setting depth, sections
Conductor	426.0	50	Isolation of unstable rocks of quaternary deposits, increasing the durability of casing string for longitudinal stability in the permafrost interval, and it is cemented to the wellhead.
Surface casing	323.9	480	The purpose and setting depth is selected with the condition of isolating permafrost rocks. The surface casing prevents hydraulic fracturing of rocks near the shoe in case of a gas blowout from Cenomanian strata (PK_1) during drilling for the intermediate casing. Surface casing increases the durability of casing string for longitudinal stability in the permafrost interval and prevents rocks from melting and failure. It also prevents from caving of rocks of the Oligocene and upper part of the Cretaceous systems in the process of drilling for intermediate string and provides isolation of groundwater of the Anthropogenic-Oligocene complex. The shoe of the casing string is installed in the interlayer of hard clays.
Intermediate casing	244.5	1100	The setting depth of the intermediate casing is selected to provide isolation of upper gas horizons, which lie in the interval of 505-1013m (vertical depth) and to cover unstable rocks, including the upper Yarong suite. Another purpose of intermediate casing is to provide compatibility of conditions for drilling for production casing with BOP on the wellhead. Intermediate casing increases the durability of casing string for longitudinal stability in the permafrost interval. The shoe of the casing string is installed in the interlayer of hard clays.

Production casing	177.8	2110	Production casing provides exploitation of development target, disconnects all productive horizons from each other, and protects from fluid cross-flows between beds. Production casing increases the durability of casing string for longitudinal stability in the permafrost interval.

Borehole profile and trajectory

A borehole profile is designed by taking into account the conditions of its further exploitation (Figiel et al., 2020; Saga et al., 2020; Dodok et al., 2017). It should be technically feasible using current technical means and provide passableness for geophysical devices, casing and drilling strings.

On the base of the geological section and drilling equipment, the designed profile includes several intervals: one vertical interval, one zenith angle buildup section, two hold sections and one zenith angle drop section. (Table 2, Figures 2, 3).

Vertical section – 0 - 550 m.

The first buildup section is made with a buildup rate of 1.0º per 10 m. On the depth of 891 m zenith angle reaches 36,50°. The radius of curvature is R = 486 m.

Hold section is located on the vertical depth of 891 - 1396 m (915 - 1543 m – drilled depth).

Zenith angle drop section with a drop-off rate of 1,0° per 10 m is drilled in the interval of 1396 - 1584 m – vertical depth (1543 - 1753 m – drilled depth). Zenith angle decreases from 36.50° to 15.0°.

Then the 2nd hold section is drilled to the bottom, zenith angle remains 15.0°.

If this type of well profile is provided, the bottom hole deviation along the top of the J2-6 is 700 m, the angle of entry of the wellbore into the productive formation will be 15.0°, and the total well deviation at the end of drilling will be 718 m.

Orienting the deviator and control over well trajectory:

- during drilling for an intermediate casing of 245 mm Russian telesystem AT-3(31) of oil research and production company "EKHO" or imported telesystem MWD-1200 "Sperry-Sun" can be used
- during drilling for production casing of 178 mm Russian telesystem AT-3(31) of oil research and production company “EKHO” or imported telesystem MWD-1200 “Sperry-Sun” can be used

Table 2. Initial data for calculation of borehole profile

Sequence number	Parameter name	Measurement unit	Value
1	Vertical depth of:	m	
	- kick-off point		550
	- end of 1st hold section		1396
	- top of J_{2-6} layer		2040
	- well		2110
	- downhole pumping equipment setting (ESP)		1950
2	Designed rate of zenith angle changing in:	degree per 10 m	
	- buildup interval		1.00
	- drop-off interval		1.00
3	The angle of entry in layer J_{2-6}	degree	up to 15
	The designed radius of curvature of:	m	
	- buildup section		573
	- drop-off section		573
4	Deviation of bottom from the top of layer J_{2-6}	m	700
5	Maximum allowed rate of change:		
	- of zenith angle:		
	in buildup section	degree per 10 m	1.5
	in drop-off section	degree per 10 m	1.5
	- of submersible pump operation	degree per 100 m	3.0
	- space angle in:		
	buildup section	degree per 10 m	2.0
	drop-off section	degree per 10 m	2.0
	sections of submersible pump operation	degree per 100 m	4.0

Table 3. Profile of directional well

Project data

Well: Novoportovskoe
Ap= 80 m
r, m 40 m
Deviation 700 m
On depth 2040 m
Magn. az 10 °
Dir. angle 22 °

(+) from wellhead relatively to vertical axis
(-) to wellhead relatively to vertical axis

Vertical depth, m	Drilled depth, m	Zenith angle °	Zenith angle ′	Azimuth, °	Direc. angle °	Elongation, m	Deviation, m	Coordinates, m X_i	Coordinates, m Y_i	Coordinates, m Z_i	angle "brackets" close edge	angle "brackets" center	angle "brackets" remote edge	azim. "brackets" ° center	azim. "brackets" ° ±	Entering the target on depth, m	Entering the target deviat., m
550,0	550	0,00		10,00			0,0	0,0	0,0	-470,0	24	25	26	10	3	2040,0	700,0
560,0	560	1,00		10,00	22	0,0	0,1	0,1	0,0	-480,0	24	25	27	10	3	2040,1	687,0
659,5	660	11,00		10,00	22	0,5	10,5	9,8	3,9	-579,5	25	27	28	10	3	2048,2	544,4
755,6	760	21,00		10,00	22	4,4	38,1	35,3	14,3	-675,6	26	27	29	10	3	2096,2	293,6
845,5	860	31,00		10,00	22	14,5	81,9	76,0	30,7	-765,5	26	27	29	10	4	2189,1	35,4
891,2	915	36,50		10,00	22	23,8	112,5	104,3	42,1	-811,2	25	27	29	10	4	2296,7	180,1
891,3	915,2	36,50		10,00	22	23,9	112,6	104,4	42,2	-811,3	25	27	29	10	4	2344,1	262,6
1396,4	1543,5	36,50		10,00	22	147,1	486,3	450,9	182,2	-1316,4	15	18	22	10	11	2344,1	262,6
1404,5	1553,5	35,50		10,00	22	149,0	492,2	456,4	184,4	-1324,5	15	18	21	10	11	2339,0	253,9
1412,7	1563,5	34,50		10,00	22	150,8	498,0	461,7	186,5	-1332,7	14	18	21	10	11	2329,3	237,2
1421,0	1573,5	33,50		10,00	22	152,5	503,5	466,9	188,6	-1341,0	14	18	21	10	12	2320,2	221,1
1429,4	1583,5	32,50		10,00	22	154,1	509,0	471,9	190,7	-1349,4	14	17	21	10	12	2311,6	205,5
1437,9	1593,5	31,50		10,00	22	155,6	514,3	476,8	192,7	-1357,9	14	17	21	10	12	2303,5	190,6
1446,4	1603,5	30,50		10,00	22	157,1	519,4	481,6	194,6	-1366,4	13	17	20	10	12	2296,0	176,1
1455,1	1613,5	29,50		10,00	22	158,4	524,4	486,3	196,5	-1375,1	13	17	20	10	13	2288,9	162,1
1463,8	1623,5	28,50		10,00	22	159,7	529,3	490,8	198,3	-1383,8	13	17	20	10	13	2282,3	148,7
1472,7	1633,5	27,50		10,00	22	160,8	534,0	495,1	200,0	-1392,7	13	16	20	10	14	2276,1	135,6
1481,6	1643,5	26,50		10,00	22	161,9	538,5	499,3	201,7	-1401,6	12	16	20	10	14	2270,2	123,1
1490,6	1653,5	25,50		10,00	22	162,9	542,9	503,4	203,4	-1410,6	12	16	20	10	14	2264,8	110,9
1499,6	1663,5	24,50		10,00	22	163,9	547,1	507,3	205,0	-1419,6	12	16	20	10	15	2259,7	99,1
1508,8	1673,5	23,50		10,00	22	164,7	551,2	511,1	206,5	-1428,8	12	16	20	10	15	2255,0	87,7
1518,0	1683,5	22,50		10,00	22	165,5	555,1	514,7	207,9	-1438,0	11	16	20	10	15	2250,6	76,7
1527,2	1693,5	21,50		10,00	22	166,3	558,9	518,2	209,4	-1447,2	11	15	19	10	16	2246,5	66,0
1536,6	1703,5	20,50		10,00	22	166,9	562,4	521,5	210,7	-1456,6	11	15	19	10	16	2242,7	55,7
1546,0	1713,5	19,50		10,00	22	167,5	565,9	524,7	212,0	-1466,0	11	15	19	10	17	2239,2	45,7
1555,4	1723,5	18,50		10,00	22	168,1	569,1	527,7	213,2	-1475,4	11	15	19	10	17	2236,0	36,0
1564,9	1733,5	17,50		10,00	22	168,6	572,2	530,5	214,4	-1484,9	10	15	19	10	17	2233,0	26,6
1574,5	1743,5	16,50		10,00	22	169,0	575,1	533,3	215,4	-1494,5	10	15	20	10	18	2230,3	17,5
1584,1	1753,5	15,50		10,00	22	169,4	577,9	535,8	216,5	-1504,1	10	15	20	10	18	2227,8	8,6
1593,8	1763,5	15,00		10,00	22	169,7	580,5	538,2	217,5	-1513,8	10	15	20	10	19	2226,0	2,2
2040,4	2225,9	15,00		10,00	22	185,5	700,2	649,2	262,3	-1960,4	below target	below target	below target	below target		below target	
2110,3	2298,3	15,00		10,00	22	188,0	718,9	666,6	269,3	-2030,3	below target	below target	below target	below target		below target	

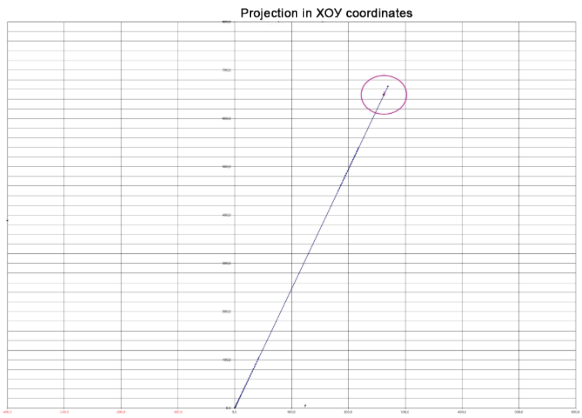

Figure. 2 Projection in XOY coordinates

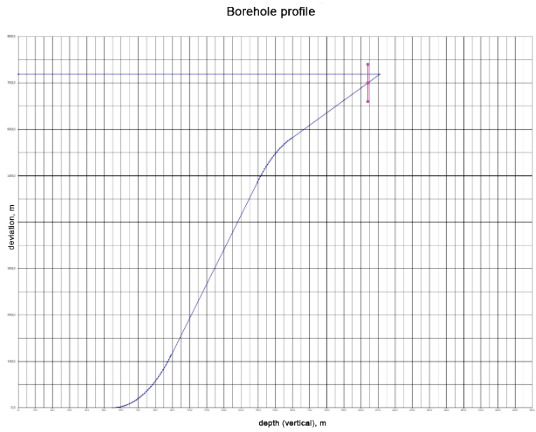

Figure 3. Borehole profile

The diameter of production casing is determined by taking into account well flow rate, size of equipment, which should be lowered in this string to provide a designed flow rate, logging results and drilling experience on the oilfield:

$$D_b = d_{cc} + 2\delta \quad (3)$$

where D_b - bit diameter, mm; d_{cc} - external diameter of casing coupling, mm; δ - radial clearance between casing coupling and borehole walls, mm.

For casing string with a diameter of 178 mm - $d_{cc} = 188\ mm$; $\delta = 10 \div 20\ mm$.

$D_b = 188 + 20 = 208\ mm$; So we choose the bit with diameter: D_b = 220 mm

Surface casing diameter is selected from condition to provide unobstructed passage of BHA, using the formula:

$$d_{in} = D_b + 2\Delta \quad (4)$$

where Δ - radial clearance between the bit and casing pipe walls, it is usually accepted in the range of 3 to 10 mm.

$d_{in} = 220 + 2 \cdot 5 = 235$ mm. We set the surface casing diameter as 245 mm.

Choosing the bit:

$D_b = 270 + 25 = 295\ mm$. We select the bit with a diameter of D_b = 295.3 mm.

The same way we calculate intermediate casing string:

$d = 295.3 + 2 \cdot 5 = 305.3$ mm. We choose a conductor casing diameter of 324 mm.

Db=351+40=391 mm. So we selected the bit with a diameter of 393.7 mm.

Calculation of conductor casing:

$d = 393{,}7 + 2 \cdot 5 = 4053{,}7mm$. We accept a conductor casing diameter of 426 mm.

D_b = 426 + 40 = 466 mm. The bit of 490 mm is selected.

The minimum setting depth for the surface casing is determined from the condition of prevention from hydrofracturing of rocks near the shoe in the process of liquidation of possible oil, gas and water shows.

When drilling from under the surface casing and opening the gas layer PK_1, above which there are no oil and water reservoirs in the section, it is necessary to lower the conductor to a depth that excludes the possibility of rock fracture after complete replacement of the drilling fluid in the well with gas and sealing the wellhead.

When calculating the casing strings of gas wells, in which there is only a gas column when the wellhead is closed, the internal pressure at the casing shoe and the intermediate string is determined by the formula:

$$Pin_{Lc} = \frac{P_{res}}{e^S}; \text{ when } 0 \le Z \le \ell_{top}$$

where $P_{пл}$ – reservoir pressure, kgf/cm^2; ℓ_{top} – depth of the top of layer, m;

$S = 0{,}1 \cdot \gamma \cdot 10^{-3}(\ell_{kr} - Z)$;

L_c – surface casing setting depth (intermediate casing), m

If $\ell_{top} \le 1000$m and $P_{res} \le 100$ kgf/cm^2 or $P_{res} \le 40$ kgf/cm^2 and any ℓ_{top}, it can be assumed that inner pressure along the whole length of the well is equal to reservoir pressure.

During drilling below the intermediate casing, gas layers are penetrated with oil and beds and aquifers are located above them (Kuric et al., 2020). Therefore, it is necessary to lower the intermediate casing to the depth, excluding any possibility of rock fracturing after full displacement of drilling mud in a well by the mixture of fluids from different horizons and wellhead sealing.

In casing strings of oil and gas wells there are both oil and gas columns inside when the wellhead is closed. The following formulas are used for calculating internal pressure near the shoe of such intermediate string:

when $H \le Z \le \ell_{kr}$

$$Pin_{L\,c} = P_{res} - 0{,}1 \times \gamma_в \times (\ell_{top} - L_c);$$

and with $0 \le Z \le H$ (5)

$$Pin_{Lc} = \frac{P_{res} - 0{,}1 \times \gamma_в \times (\ell_{top} - H)}{e^s};$$

where P_{res} – reservoir pressure, kgf/cm^2; $\gamma_в$ – fluid mixture density, g/cm^3; ℓ_{top} – top of layer, m; H – height (discharge) of gas column when BOP is closed;

$S = 0{,}1 \cdot \gamma \cdot 10^{-3} (H - Z)$;

L_c – surface casing setting depth (intermediate casing), m.

To provide safe penetration and drilling of gas deposit in layer PK1 of the Marresaline Suite (505 – 513 m), it is necessary to lower the surface casing to its top L_c = 480 м and install BOP.

Surface casing setting depth is checked (worst conditions) with gas deposit TP_0 with ℓ_{top} = 998 m, P_{res} = 100 kgf/cm^2, γ = 0,645 g/cm^3, H = 998 m.

According to clause 4.2 of instruction (Ivanova et al., 2018; Ivanova et al., 2018; Savenok et al., 2020), in case of gas shows and full displacement of drilling mud by gas, internal pressure near the shoe of surface casing will be:

$Pin_{480} = Pres_{998} = 100$ kgf/cm^2

if $\ell \le 1000$ m and $P_{res.}\ell \le 100$ kgf/cm^2 internal pressure from the top of the layer to the wellhead is accepted as equal to reservoir pressure.

Hydrofracturing pressure near surface casing shoe:

$P_{fr\ 480} = 0.22 \times 480 = 105.6$ kgf/cm^2.

Safety factor for rock fracturing in case of Cenomanian gas blowout and closed wellhead with BOP will be:

$$\eta = \frac{105.6}{100} = 1.056$$ (i.e. 5.6%), which is enough.

The main criterion for selection of intermediate casing setting depth is providing compatible drilling conditions:

- casing string is lowered to cover gas deposits in the interval of 505 - 1013 m (PK_1, HM_1, HM_3, TP_0, TP_{1-4}) with shoe installation on the vertical depth of 1100 m;

- providing the possibility of further drilling for production string with lighter polymer-carbonate drilling mud.

While drilling for production casing string, aquifers, gas, and oil-saturated layers will be penetrated; their anomaly ratio is Ka = 1.0.

Maximum wellhead pressure occurs in case of gas shows and full displacement of drilling mud by the mixture of liquid and gas (gas, oil, water) and its division into gas and liquid columns after closing the wellhead with BOP. For the calculation, we use worst conditions from gas layer J $_{2\text{-}6}$: $\ell_{top.} = 2025$ m, $P_{res} = 203$ kgf/cm^2, $\gamma = 0.685$ g/cm^3, $\gamma_н = 0.72$ g/cm^3, $K_a = 1.0$; $H = 0.6\ \ell_{top} \approx 1200$ m

In case of gas shows and if the wellhead is closed, the internal pressure at the intermediate casing shoe will be:

$P_{in\ L\ in.c} = [203 - 0.1 \cdot 0.72 \cdot (2025 - 1200)]\boldsymbol{:}\ \boldsymbol{e}^{s} \approx 144$ kgf/cm^2 ,

where: $S = 0{,}1 \cdot \gamma \cdot 10^{-3}(\ell_{top} - Z) = 0.1 \cdot 0.685 \cdot (1100 - 1100) = 0$, $\boldsymbol{e}^{s} = 1{,}0$

The intermediate casing string setting depth accepted in the project is 1100 m; it meets the requirements of clause 26 of the design task and takes into account zones of compatible drilling conditions and the geological structure of the section.

Check calculation of intermediate casing string setting depth for the condition of prevention from rock hydrofracturing near the shoe:

- fracturing pressure of rocks near the shoe of intermediate casing string will be:

$$P_{fr1100} = 0.18 \cdot 1100 = 198 \text{ kgf/cm}^2;$$

- internal pressure near the shoe of intermediate casing string in case of oil shows and closed wellhead:

$Pin\ 1_{1100} = 144$ kgf/cm^2 .

The safety factor of rocks for fracturing:

$$\eta = \frac{198}{144} = 1.37\ (i.e.\ 37\%)$$, which is enough.

Calculation of drill collar includes finding its diameter and length. The diameter of the drill collar is found on the base of provision the highest stiffness of the cross-section in given drilling conditions. The length of the drill collar takes into account the load on the bit

Considering that the production string is drilled with a bit of 220.7 mm diameter, we selected a drill collar of 178 mm diameter.

$$\frac{D_{dc}}{D_b} = \frac{178}{220{,}7} = 0.81 \tag{6}$$

This value is in the range of 0.80 – 0.85, and it does not exceed the diameter of the screw downhole motor (195 mm). The drill collar diameter corresponds to existing recommendations and provides necessary stiffness.

The length of drill collar is found according to the formula:

$$l_{dc} = \frac{1{,}25 \cdot P_b - G}{q_{dc}}; \tag{7}$$

where P_b – load on bit (10 tons = 10000 kg),

G – the mass of the screw downhole motor (1313 kg),

q_{dc} – drill collar weight per meter (156 kg).

$$Ldc = \frac{(1.25 \cdot 0.10) - 0.01313}{0.00156} = 71.71\text{m}$$

We accept that $L_{dc} = 75м$, i.e. three stands with a length of 25 m.

Drill collar weight $Q_{dc} = 75 \cdot 0{,}00156 = 0{,}117MN = 11{,}7t$.

The drill string diameter is selected according to the diameter of the previous casing string, which is 245mm. For this case, the diameter of the drill string is accepted as 127 mm. The check of the ratio of the diameter of drill pipes, located above drill collar to the diameter of drill collar itself:

$$\frac{D_{dp}}{D_{dc}} = \frac{127}{178} = 0{,}71 \tag{8}$$

In this case, the condition is fulfilled: $\frac{D_{dp}}{D_{dc}} \geq 0{,}70$

Allowable setting depth of drill pipes is found according to the formula:

$$l_{allow} = \frac{Q_p - k(Q_{dc} + G)\left(1 - \frac{\rho_{dm}}{\rho_м}\right) - (\rho_0 - \rho_n)F_k}{kq_{бт}\left(1 - \frac{\rho_{dm}}{\rho_м}\right)} \tag{9}$$

Allowable setting depth of drill pipes with a diameter of 127 mm is found the following way. As we select steel of strength grade «L», we know that pipe walls thickness is 9.19 mm; the weight of the one-meter of string $q_{БТ}$ is 31.9 kg; tensile load, under which the load in the body of steel drill pipe SDP-127 with strength grade "L" reaches yield strength, is $Q_{yield} = 2.15MN$. We accept $n = 1.3$ – safety factor for normal drilling conditions; $k = 1.15$ – coefficient considering the influence of friction, inertion and resistance to movement of drilling mud; G (weight of screw downhole motor DRU1-195RS) = 1313 kg. Other data for calculation include ρ_{dm} – drilling mud density; for drilling of the last section, it is 1.13 g/cm^3; ρ_M – pipe material density, 7.85 g/cm^3; p_0 – pressure difference on the bit, 2.0 MPa; p_n – pressure difference on screw downhole motor, 1,0 MPa; area of flow section of pipes $F_k = \frac{\pi D^2}{4} = 0.785 \cdot 0,10862 = 0,009 m^2$. Firstly, we find an allowable tensile load for pipes of the lowest section in normal drilling conditions Q_p:

$$Q_p = \frac{Q_{yield}}{n} = \frac{2,15}{1,3} = 1,65 MN$$

$$L_{allow} = \frac{1.65 - 1.15(0.117 + 0.01313)\left(1 - \frac{1.13}{7.85}\right) - (2-1) * 0.009}{1.15 * 0.000319 * \left(1 - \frac{1.13}{7.85}\right)} = 4818.12 \text{ m}$$

Pressure losses in drill string:

$$\Delta p_{ds} = \frac{8}{\pi^2} * \lambda_{ds} * \frac{L}{d^5} * \rho * Q^2 \quad (10)$$

λ_{bk} - hydraulic resistance coefficient, which depends on mud flow mode.

$$\Delta p_{ds} = \frac{8}{3.14^2} \cdot 0,0281 \cdot \frac{2343}{0.109^5} \cdot 1050 \cdot 0.03^2 = 4.2 \text{ MPa}$$

Pressure losses in the circular clearance of borehole are found using the formula:

$$\Delta p_{kz} = \frac{8}{\pi^2} \cdot \lambda_{ds} \cdot \frac{L \cdot \rho \cdot Q^2}{(D-d)^3 \cdot (D+d)^2} \quad (11)$$

$$\Delta p_{cc} = \frac{8}{3.14^2} \cdot 0.0426 \cdot \frac{2343 \cdot 1050 \cdot 0,03^2}{(0.220 - 0.127)^3 \cdot (0.220 + 0.127)^2} = 0.77 \text{ MPa}$$

Pressure losses in the circular clearance of surface casing are found using the formula:

$$\Delta p_{cc} = \frac{8}{\pi^2} \cdot \lambda_{cc} \cdot \frac{L \cdot \rho \cdot Q^2}{(D-d)^3 \cdot (D+d)^2} \quad (12)$$

$$\Delta p_{cc} = \frac{8}{3.14^2} \cdot 0.045 \cdot \frac{71.71 \cdot 1050 \cdot 0.03^2}{(0.225 - 0.127)^3 \cdot (0.225 + 0.127)^2} = 0.21 \text{ MPa}$$

Total pressure losses in circulation system of a well (without the bit):

$$\Delta P = \Delta PDM + \Delta PDS + \Delta PCC + \Delta PM \quad (13)$$

$$\Delta P = 4,5 + 4,2 + 0,77 + 0,21 + 0,0252 = 9,70 \text{ MPa}$$

Drilling methods and modes are demonstrated in table 4.

Table 4. Methods of drilling, borehole over-reaming and main parameters of performance of this technological operation

Interval, m				Type of technological operation	Drilling method	BHA identification number	Drilling mode				Speed of performance of the technological operation, m/h
vertical		drilled					Axial load, t	Rotor speed, rpm	Torque (reaction) considering friction forces, kgf·m	Drilling mud flowrate, l/s	
from (top)	to (bottom)	from (top)	to (bottom)								
1.1. Drilling for conductor casing ∅ 426 mm:											
0	50	0	50	Drilling, reaming (wiper trip)	rotary	1		65÷80	200	55.12	25÷30
1.2. Drilling for surface casing Ø324 mm:											
45	52	45	52	Drilling cement plug, conductor shoe	turbine	2	2÷5	-	-	55.12	10÷15
52	190	52	190	drilling	turbine	3	5÷12	-	-	55.12	35÷30
190	480	190	480	drilling	turbine	3	5÷12	-	-	55.12	30÷25
50	480	50	480	reaming (wiper trip) before lowering the surface casing, reaming before logging (in case of troubles)	turbine	4	7÷10	-	-	55.12	100÷120

1.3. Drilling for intermediate casing Ø 245 mm:											
470	482	470	482	Drilling cement plug, cementing throttle check valve, surface casing shoe	turbine	5	2÷5	-	-	50.53	10÷15
482	505	482	505	drilling	turbine	6	2÷10	-	-	50.53	30÷35
505	700	505	702	drilling	turbine	6	2÷10	-	-	50.53	25÷30
700	1100	702	1175	drilling	turbine	6	2÷10	-	-	50.53	22÷25
480	1100	480	1175	reaming (wiper trip) before lowering the intermediate casing, reaming before logging (in case of troubles)	turbine	7	7÷10	-	-	50.53	100÷120
1.4. Drilling for production casing ∅ 178 mm:											
1092	1102	1165	1177	Drilling cement plug, cementing throttle check valve, intermediate casing shoe	turbine	8	2÷5	-	-	34.45	10÷15
1102	1350	1177	1486	drilling	turbine	9	2÷10	-	-	34.45	35÷45
1350	1720	1486	1934	drilling	turbine	9	2÷10	-	-	34.45	30÷35
1720	1990	1934	2218	drilling	turbine	9	2÷10	-	-	34.45	25÷30
1990	2110	2218	2343	drilling	turbine	9	2÷10	-	-	34.45	20÷25
1831	1854	2054	2077	Core sampling in 1/10 of the well	turbine	11	2÷5	-	-	24.8	2÷4
2025	2060	2254	2290	-"-	turbine	11	2÷5	-	-	24.8	2÷4
1100	2110	1175	2343	(wiper trip) before lowering the casing, reaming before logging (in case of troubles)	turbine	10	7÷10	-	-	34.45	100÷120
1.5. Operations inside the production casing Ø178 mm:											
-	950	-	989	Drilling stage cementing device USC-178	turbine	12	1÷3	-	-	12÷18	0.5÷1

Let us determine the type of drill pipes, their diameter and the type of tool joints:

$$d_{dp} = 0{,}5 \cdot 220 = 110 \text{ mm},$$

therefore, we select internal-external upset (IEU-127mm).

Steel drill pipes IEU-127x9,19 with strength grade "D" meet the condition of a smooth transition from drill collar to drill string.

Allowable setting depth of a string made of pipes with similar wall thickness:

$$l_{allow} = \frac{Q_p - k(Q_{dc}+G)\left(1-\frac{p_{dm}}{p_M}\right) - (p_o+p_n)F_{ch}}{kq_{dc}\left(1-\frac{p_{dm}}{p_M}\right)}, \quad (14)$$

In which Q_p – allowed tensile load, it is found according to the formula:

$$Q_p = \frac{\sigma_T F_{fr}}{n} = \frac{Q_{ult}}{n}, \quad (15)$$

where n – strength safety factor (1.3 – value for normal drilling conditions 1.35 – for complicated);

Q_{ult} = 1.15 MN – ultimate load;

F_{fr} = 33.4 cm^2 = 3340 mm^2 – area of section;

$Q_p = \frac{1.15}{1.35} = 0{,}8518519$ MN;

K=1.15 – coefficient taking into account the influence of friction forces, inertion and resistance to movement of drilling mud;

$Q_{dc} = 75 \cdot 0{,}00156 = 0{,}117\text{MN} = 11{,}7\text{t}$ – the weight of 100 meters of drill collar 172x49;

P_{dm} = 1.05 g/cm^3 – density of drilling mud for lower intervals;
$\rho_м$ = 7.85 g/cm^3 - density of drill pipe material;

$$q_{dp} = \frac{l \times q_1 + q_2 + q_3}{l}, \quad (16)$$

where l = 12.5 m - pipe length;
q_1 = 29 kg - mass of 1 m of plain pipe;
q_2 = 7 kg – weight of upset ends;
q_3 = 65 kg – weight of one tool joint.

$$q_{dp} = \frac{12.5 \times 29 + 7 + 56}{12.5} = 31.9 \text{ kg} = 0{,}000319\text{MN}.$$

F_{ch} = 92.6 cm^2=0.00926 m^2 – area of pipe flow channel;
P_o = 7 MPa – maximum pressure difference in 5LZ172Dx7.0LL;
P_n = 5 MPa – pressure difference on the bit.
Calculation of maximum setting depth for casing string:

$$L_{allow} = \frac{1.65 - 1.15(0.117 + 0.01313)\left(1 - \frac{1.13}{7.85}\right) - (2-1)\cdot 0.009}{1.15 * 0.000319 * \left(1 - \frac{1.13}{7.85}\right)} = 4818.12 \text{ m}$$

These drill pipes are suitable because the drilled depth of the well will be 2343 m.
Drill string length:

$$l_{dp} = L_{dps} - l_{dc}, \quad (17)$$

$$l_{dp} = 2343 - 75 = 2268 \text{ m}.$$

Weight of drill pipes will be:

$$Q_{dp} = q_{dp} \times l_{dp}, \quad (18)$$

$$Q_{dp} = 2268 \cdot 0{,}000319 = 0{,}72349 \text{ MN}$$

Drilling for the conductor, surface casing and production casing is planned to make by means of Russian drill pipes with a diameter of 127 mm and wall thickness of 9ю19 mm made of steel "L" (GOST 50278-92 or TR 14-161-219-2004), and drill collars with a diameter of 203 mm, 178 mm according to TR 51-744-77 (Elbakian et al., 2018).

Selection of drilling rig

On the base of the calculations mentioned above, to drill a well with a depth of 2343 m, we need to take 75 m of drill collars and 2268 m of drill pipes with strength grade "L" and wall thickness of 9.19 mm.

Weight of steel drill pipes: $Q_{dp} = 2268 \cdot 0{,}000319 = 0.72349$ MN

Weight of the whole drill string: $Q = 0.117 + 0.72349 = 0.84049$ MN

Weight of production string: 0.91940MN

According to oil and gas industry safety rules and regulations, the drilling rig is selected according to allowable hook load: the most weighted drill string or casing string should not exceed this value. The safety factor for drill string is 0,6; for casing string – 0,9. In our case, the biggest weight has the casing string - 0,91940 MN. Applying safety factor 0.9, we get a hook load of 1,02156 MN. On the base of that, we select a drilling rig from GOST 16293-89. In our case, it is a drilling rig of 4 grade BU-3200/200 EK_BM.

Drilling muds

Since the well section consists of sandstone and clay packs, liable to loss of stability with a decrease in back pressure, sticking during a long shutdown of the well during drilling. But there are no areas with anomaly high reservoir pressures in the well, and there are no high temperatures, so it is most reasonable to use a clay bentonite solution for drilling a well under such conditions. To avoid complications while drilling wells, we introduce stabilizing reagents to maintain the required mud parameters.

Substantiation of the density of applied drilling muds

The density of drilling muds for intervals of compatible drilling conditions is calculated from the condition of saving stability of rocks. As for intervals with high-pressure layers, mud density should be selected to create sufficient hydrostatic pressure on the bottom by the mud column and prevent reservoir fluids from entering in borehole:

$$\rho = \frac{100 * P_{res} * k}{H}; \tag{19}$$

where $k = 1{,}10 \leq 1200m;\ k = 1{,}05 \geq 1200m$

Drilling mud density for each interval:

$$\rho_{cond} = \frac{100 \cdot Pres \cdot k}{H} = \frac{100 \cdot 0.5 \cdot 1.1}{50} = 1.1\ \frac{g}{cm^3}$$

$$\rho_{surf.cas} = \frac{100 \cdot Pres \cdot k}{H} = \frac{100 \cdot 4.8 \cdot 1.1}{480} = 1.1\ \frac{g}{cm^3}$$

$$\rho_{prod1} = \frac{100 \cdot Pres \cdot k}{H} = \frac{100 \cdot 11 \cdot 1.05}{1100} = 1.05\ \frac{g}{cm^3}$$

$$\rho_{prod2} = \frac{100 \cdot Pres \cdot k}{H} = \frac{100 \cdot 21.1 \cdot 1.05}{2110} = 1.05\ \frac{g}{cm^3}$$

For the interval from 0 to 1200 m hydrostatic pressure, created by drilling mud column, should be at least 10% higher than reservoir (pore) pressure. Reservoir pressure in this interval is normal (anomaly ratio is K_a = 1.00).

Consequently, drilling mud density in mentioned interval should be at least 1.10 g/cm^3. What is more, hydrostatic pressure can exceed reservoir pressure by 15 kgf/cm^2. To provide stability of borehole walls, the designed density of drilling mud for conductor and surface casing is 1.16-1.18 g/cm^3, for the intermediate casing – 1.20 g/cm^3. These values were set, taking into account penetration of PK_1 layer and experience of drilling in similar conditions.

For drilling intervals from 1200 m to the target depth, hydrostatic pressure of the drilling mud column should be at least 5% higher than reservoir pressure, but the difference should not exceed 25 - 30 kgf/cm^2.

Reservoir pressure in this interval is normal (K_a = 1.00).

Thus, for drilling in the interval of 1200 – 2110 m, the density of drilling mud should be at least 1,05 g/cm^3, but in view of the interval of compatible drilling conditions (1100 - 2110 m), mud density should be at least 1,10 g/cm^3. Drilling mud density, accepted in the project of drilling for production casing, is 1.10 - 1.13 g/cm^3 (Tables 5, 6).

The overbalance applied to borehole walls does not exceed the allowable value (maximum allowable mud density for J2-6 layer – 1.15 g/cm^3).

Table 5. Types and parameters of drilling muds

Drilling mud type	Interval, m				Drilling mud parameters											
	vertical		drilled		density, g/cm3	relative viscosity, s	fluid loss, cm^3/30 min	filter cake thickness, mm	static shear stress, qPa after		pH	plastic viscosity, mPa·s	Dynamic shear stress, qPa	sand content, %	mud filtrate salinity, g/l	temperature on the inlet, degrees
	from (top)	to (bottom)	from (top)	to (bottom)					1 minute	10 minutes						
1. Drilling for conductor ∅ 426 mm:																
Polymer-clay mud	0	50	0	50	1.16-1.18	55-80	6	1.5-1	35-40	70-100	8-9	35-45	30-55	before 1.5-2	0.2	8-10
2. Drilling for surface casing ∅ 324 mm:																
Polymer-clay mud	50	480	50	480	1.16-1.18	55-80	6	1.5-1	35-40	70-100	8-9	35-45	30-55	before 1.5-2	0.2	8-10
3. Drilling for intermediate casing ∅ 245 mm:																
Polymer-clay mud	480	1100	480	1175	1.20	30-35	6	1.0	15-20	30-35	8-9	20-24	25-35	before 1.0-1.5	before 1.5-3.0	
4. Drilling for production casing ∅ 178 mm:																
Polymer-carbonate mud	1100	2110	1175	2343	1.10-1.13	Parameters of polymer-carbonate mud (PCM) are shown in Table 6										

Table 6. Total consumption of drilling mud components

Component name	Component consumption, t				
	Name of the casing string				Total for well
	conductor	surface casing	intermediate casing	production casing	
Modified bentonite powder (PBMA)	20.000	24.940	6.950	—	51.890
KMC-600,700	0.050	0.344	0.278	—	0.672
Sodium carbonate Na2CO3	0.127	0.484	0.359	0.099	1.069
FK-2000	—	0.172	0.208	—	0.380
Pentor-2001	—	0.043	0.069		0.112
Kem-Pas	—	—	0.208	—	0.208
Poly-Kem-D	—	—	0.069	—	0.069
Barite (UBPM-1) q=4,25 г/см^3	—	—	15.290	—	15.290
NTP	—	—	0.021		0.021
Duo-Vis	—	—	—	0.712	0.712
Hibtrol	—	—	—	1.775	1.775
Poly Pac UL	—	—	—	1.051	1.051
Poly Pac R	—	—	—	0.771	0.771
Defoam-x (anti-foaming agent)	—	—	—	0.105	0.105
Kla Cure	—	—	—	0.245	0.245
Drill Free	—	—	—	0.444	0.444
M-I-Cide	—	—	—	0.491	0.491
"Lo-Wate" (CaCO3, F)	—	—	—	26.774	26.774
"Lo-Wate" (CaCO3, M)	—	—	—	9.800	9.800
NaOH		—	—	0.771	0.771

Summary

The technology of drilling slant exploitation well in the oilfield of Western Siberia has been studied. Development of well construction has taken into account the next geological features of the section: permafrost rocks occur to the depth of 260 m, and iciness also takes place. Well construction is selected on the base of intervals of incompatible drilling conditions. The designed profile includes several intervals: one vertical interval, one zenith angle buildup section, two hold sections and one zenith angle drop section. A check calculation of the setting depth of the intermediate casing for the condition of preventing hydraulic fracturing of rocks near the shoe was carried out, and the safety factor of rocks for hydraulic fracturing was found. Drill pipes calculation includes determination of their length and diameter as well as allowable setting depth for drill pipes. This article demonstrates drilling methods, borehole under-reaming methods and the main parameters for the performance of technological operations of directional drilling. A drilling rig has been selected according to the allowable hook load. The density of the used drilling muds has been substantiated for the intervals of compatible drilling conditions, types and parameters of muds.

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