Nafta-Gaz 2023, no. 6, pp. 398–405, DOI: 10.18668/NG.2023.06.03

Factors affecting the sand plug formation process in controlled directional wells

Czynniki wpływające na proces piaszczenia w odwiertach kierunkowych

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ABSTRACT: Many wells of offshore fields in Azerbaijan are subject to sanding and plugging. This is especially observed in wells at a late stage of development. The process of plug formation in directional wells is known to be characterized by a variety of factors associated with both natural conditions and the parameters of their development and, most importantly, operation. The degree of influence of the factors varies, in addition to the fact that all of them (directly or indirectly) are interconnected. Sand production is often observed during completion (development) and operation of wells, especially when the productive reservoirs are represented by weakly cemented rocks. It is worth noting that in the case of sand plug formation, the permeability of which is 200 times greater than the permeability of the productive formation, the oil production rate decreases by 34%. This sand contains up to 5% of oil and poses a problem upon its removal, as it results in environmental contamination. In addition, it deposits in pipelines, surface equipment, causing erosion. This kind of complication is almost universal. Sand removal is one of the main reasons for the formation of cavities and collapse of columns. This problem has acquired particular relevance with the development of thermal methods for the extraction of high-viscous oils: the viscosity of oil decreases, and its fluidity increases. In this case, some reservoirs lose their cementing binder - viscous oil. During planned and emergency shutdowns, when the coolant injection stops, the reverse flow of the coolant enters the injection wells and removes mechanical impurities. This also leads to the formation of sand plugs in the wells and prevents the normal injection of the coolant. The existing methods of operating wells affected by sanding can be divided into two groups: 1) operation of wells with the removal of sand from the reservoir; 2) prevention of sand production from the formation.

Key words: sand plug, screen pipe, correlation analysis, diagnostic coefficient, watering (water cut).

STRESZCZENIE: Wiele odwiertów w złożach zlokalizowanych w obszarze morskim w Azerbejdżanie ulega piaszczeniu i kolmatacji strefy złożowej, co nasila się zwłaszcza w odwiertach znajdujących się w końcowej fazie eksploatacji. Jak wiadomo proces kolmatacji strefy złożowej w odwiertach kierunkowych charakteryzuje się różnymi czynnikami, związanymi zarówno z warunkami naturalnymi, jak i parametrami ich udostępniania oraz, co najważniejsze, eksploatacji. Stopień wpływu tych czynników jest zróżnicowany, a wszystkie one są ze sobą powiązane, bezpośrednio lub pośrednio. Piaszczenie jest często obserwowane podczas udostępniania odwiertów, a zwłaszcza podczas ich eksploatacji, gdy interwał zbiornikowy jest reprezentowany przez skały słabo scementowane. Należy podkreślić, że w przypadku utworzenia się korka piaskowego, którego przepuszczalność może być nawet 200 razy większa niż przepuszczalność formacji złożowej, wskaźnik wydobycia ropy spada o 34%. Piasek ten zawiera do 5% ropy naftowej i stanowi duży problem w przypadku jego usuwania, ponieważ może powodować skażenie środowiska. Ponadto osadza się on w rurociągach i urządzeniach powierzchniowych, powodując ich erozję. Ten rodzaj komplikacji jest niemal powszechny. Usuwanie piasku jest jedną z głównych przyczyn powstawania kawern i zapadania się kolumn rur. Problem ten nabrał szczególnego znaczenia wraz z rozwojem termicznych metod wydobycia rop o wysokiej lepkości: lepkość ropy spada, a jej płynność wzrasta. W takim przypadku niektóre skały zbiornikowe tracą spoiwo cementujące - lepką ropę. Podczas planowanych i awaryjnych wyłączeń, gdy zatrzymywany jest wtrysk chłodziwa, następuje odwrócenie przepływu chłodziwa, w wyniku czego wpływa ono do otworów zatłaczających i usuwa zanieczyszczenia mechaniczne. To również prowadzi do piaszczenia w odwiertach i uniemożliwia normalne zatłaczanie chłodziwa. Istniejące metody eksploatacji odwiertów w takich przypadkach można podzielić na dwie grupy: 1) eksploatacja odwiertów z usuwaniem piasku ze złoża; 2) zapobieganie produkcji piasku z formacji złożowej.

Słowa kluczowe: zapiaszczenie, rura tracona perforowana, analiza korelacji, współczynnik diagnostyczny, zawodnienie (zawartość wody).

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Article contributed to the Editor: 16.01.2023. Approved for publication: 14.06.2023.

Introduction

At present, it is not possible to develop a set of measures to prevent all existing factors influencing plug formation. Therefore, it is advisable to determine one or more factors that contribute most to directional wells plugging, and then proceed to develop methods to remove or reduce their influence (Dake, 1983).

Sand production is often observed during completion and operation phases, especially when the productive reservoirs are represented by weakly cemented rocks. According to M. Muskat (1946), in the case of sand plug formation, the permeability of which is 200 times greater than the permeability of the productive formation, the oil production rate decreases by 34%.

The main parameter that determines the frequency and level of plug formation is the specific volume of washed sand plug (y). This parameter is defined as the ratio of the total volume of the flushed plug to the number of well days worked in a given horizon (Mirzajanzade and Stepanova, 1977; Mirzajanzade, 1986; Mirzajanzade et al., 1997).

Methods and discussion

When analyzing the operation of plug-forming wells, the main factors affecting the formation of a sand plug were selected:

- oil production rate (X_1 [t/day]);
- water flow rate (X_2 [m^3/day]);
- water cut of well production (X_3 [%]);
- the degree of immersion of the first row in the screen section (X_4), (determined by calculating the ratio of the length of the pipes located in the screen section to the power of the screen itself);
- oil content in the composition of products (X_5);
- upflow speed in the first row (X_7 [m/sec]);
- wellbore curvature coefficient (X_8) (the ratio of the depth of the well to the value of the vertical projection of the lines from the wellhead to the lower openings of the screen).

Finding a relationship between the main parameter (Y) and affecting factors (%) in the analysis of plug-forming wells makes it possible to (Kendell, 2018):

- determine the degree of effect of each factor and, consequently, the identification of the main factors affecting the process of plug formation (Mirzadzhanzade and Shahverdiyev, 1997);
- identify the need for a particular event in order to reduce and suppress the formation of sand plugs;
- regulate the parameters that affect the process of plug formation and allow preventing or reducing the formation of sand plugs.

To find this relationship, direct methods of analysis and research between parameters (Y) and affecting factors (X_i) are required. However, such research is limited, expensive, and in most cases (especially in offshore conditions) is not feasible.

For a comprehensive study of the issue of the influence of the main factors having the most significant impact on the operation of directional plug-forming wells, a large array of geological and field data was analyzed and the possibility of involving mathematical statistics methods in the analysis was considered (Mirzajanzade and Stepanova, 1977, Mirzajanzade et al., 1997).

Correlation analysis and a sequential diagnostic procedure can be used as statistical methods, the essence of which is described in numerous literature (Jensen et al. 2000; Mirzajanzade et al., 2002; Navidi, 2011). Let's consider the influence of the above factors on the process of sand plug formation using the geological and field data given in Table 1.

According to the correlation analysis, the dependence of the specific volume of a sand plug (Y) on the considered factors is established (Kendell, 2018). First, partial dependencies are defined, i.e. dependence (Y) on each factor ($Y = f(X_i)$), then multiple correlation equations are compiled. In this case, the factor whose influence on the value of the output parameter (Y) is insignificant, is dropped.

The results of partial dependencies are shown in Table 2. According to the table, multiple correlation equations are compiled, which have the following form:

$$Y = 16.125 \cdot 10^{-4} X_1^3 - 0.319\sqrt[3]{X_2} + 0.238\sqrt[3]{X_3} + 0.630\sqrt[3]{X_4} - 0.142 X_5^4 + 2 \cdot 10^{-4} X_6 - 0.011 X_7^{-2} + 15.943 X_8 \quad (1)$$

Calculations carried out using the MGAA method (*Method of Group Accounting of Arguments*) showed that the effect of X_4, X_5, X_6, and X_7 factors is very insignificant and can be neglected.

It should be noted that the method of group accounting of arguments (MGAA), which is a further development of the regression analysis method, has become widespread (Ivakhnenko and Muller, 1984). It is based on some principles of the theory of learning and selection, in particular directed selection ("heuristic self-organization") (Ivakhnenko, 1971).

In algorithms with linear polynomials, relations take the form

$$y_k = a_0 + a_1 x_i + a_2 y_i, \quad 0 \prec i \le m$$

where m is the number of input arguments.

The algorithm synthesizes models with a successively increasing number of arguments taken into account. Thus, the models of the first selection series include two arguments each, the models of the second series – three or four, and so on.

Among the main MGAA algorithms, the generalized algorithm is the most interesting, providing the most accurate models due to the use of additive and multiplicative trend

Table 1. Technical and operational indicators of plugging wells

Tabela 1. Techniczne i operacyjne wskaźniki kolmatacji odwiertów eksploatacyjnych

No of well	Screen	Oil / water production rate	Water cut (watering degree), X_3 [%]	The degree of immersion of pipes of the 1st row in the screen, X_4	Oil content in production, X_5	Flow rate ascending the production string, 10^{-2} m/sec, X_6	Upflow speed for 1st row of lifting pipes, 10^{-2} m/sec, X_7	Curvature factor, X_8	Specific volume of sand plug [m^3 per day]
1	1819–1791	4 / 2.5	38.5	0.036	0.615	4.55	26.0	1.6950	11.21
2	2047–1998	17 / –	–	0.330	1.000	17.00	68.0	1.1600	0.54
3	2569–2530	1 / –	–	0.100	1.000	1.00	4.0	1.2286	1.79
4	2472–2757	1 / –	–	–	1.000	1.00	4.0	1.3366	1.91
5	2698–2647	40 / –	–	–	1.000	40.00	160.0	1.2333	2.99
6	2440–2423	16 / –	–	0.410	1.000	16.00	68.0	1.3072	2.78
7	1643–1625	5 / 2	28.9	0.280	0.710	7.00	28.0	1.3366	3.94
8	1585–1572	12 / 3	20.0	0.150	0.800	15.00	60.0	1.2294	1.88
9	1787–1735	0.1 / 1	90.9	0.190	0.100	1.10	4.4	1.1399	1.83
10	2193–2137	20 / 8	28.6	–	0.710	28.00	112.0	1.1497	0.68
11	2004–1976	5 / 1	17.0	0.180	0.830	4.20	24.0	1.1970	1.60
12	2319–2287	10 / –	–	–	1.000	10.00	40.0	1.3700	4.47
13	2143–2103	1 / –	–	0.100	1.000	1.00	4.0	1.2425	2.00
14	2070–2065	1 / 10	90.9	–	0.100	11.00	44.0	1.3549	6.75
15	1933–1990	37 / –	–	0.270	1.000	37.00	148.0	1.3483	0.22
16	1675–1641	12 / 1.2	9.1	0.590	0.900	13.20	52.8	1.1262	0.12
17	2192–2159	3 / 1.2	60.0	0.570	0.200	15.00	60.0	1.3477	4.71
18	1822–1777	9 / 2	18.2	0.220	0.820	11.00	44.0	1.3722	5.41
19	2100–2030	30 / 9	23.1	0.710	0.740	39.00	156.0	1.1340	0.24
20	169–147	2 / 1	33.3	0.410	0.670	2.10	12.0	1.1438	0.89
21	171–132	2 / 1	33.3	0.130	0.670	2.10	12.0	1.1102	0.20
22	544–514	0.5 / 1	66.7	0.630	0.330	1.50	6.0	1.1110	0.56
23	729–714	20 / –	–	0.150	1.000	20.00	8.0	1.1928	1.24
24	241–292	4 / 1	20.0	0.310	0.800	3.50	20.0	1.1078	0.24
25	179–133	0.1 / 3	96.8	0.220	0.030	2.20	12.4	1.1108	0.20
26	607–599	4 / 4	50,0	0.500	0.500	8.00	64.0	1.1360	0.37
27	357–323	2 / 1	33.3	–	0.670	2.10	12.0	1.1667	1.24
28	501–472	2 / 1	33.3	–	0.670	0.30	12.0	1.1470	1.04
29	390–346	1 / 2	66.7	–	0.330	0.30	12.0	1.1667	1.84
30	512–485	14 / 2	12.5	0.410	0.875	16.00	64.0	1.1141	0.39
31	363–346	2 / 1	33.3	–	0.670	2.10	12.0	1.1203	0.63
32	387–364	8 / 2	20.0	0.610	0.800	7.00	40.0	1.1510	1.00
33	301–199	0.1 / 2	96.0	0.550	0.040	2.10	8.4	1.1255	1.51
34	556–514	3 / 4	57.0	0.140	0.430	7.00	48.0	1.1092	0.16
35	389–364	31 / 1	25.0	–	0.750	4.00	16.0	1.1203	0.23
36	959–929	1 / 4	80.0	0.330	0.200	5.00	16.0	1.1310	0.78
37	367–327	5 / 2	50.0	0.750	0.500	5.00	20.0	1.1510	1.30
38	307–279	2 / 1	33.3	–	0.667	3.00	12.0	1.1428	0.99
39	497–460	2 / 1	33.3	–	0.667	2.10	12.0	1.1719	1.42
40	706–689	5 / 7	58.3	0.290	0.420	8.40	48.0	1.1118	0.76

cont. Table 1/cd. Tabela 1

No of well	Screen	Oil / water production rate	Water cut (watering degree), X_3 [%]	The degree of immersion of pipes of the 1st row in the screen, X_4	Oil content in production, X_5	Flow rate ascending the production string, 10^{-2} m/sec, X_6	Upflow speed for 1st row of lifting pipes, 10^{-2} m/sec, X_7	Curvature factor, X_8	Specific volume of sand plug [m^3 per day]
41	701–659	2 / 1	33.3	0.500	0.667	2.1	12.4	1.1124	0.51
42	322–250	3 / 1	25.0	0.320	0.750	4.0	16.0	1.1837	1.42
43	568–558	12 / 3	20.0	0.300	0.800	15.0	60.0	1.2640	2.53
44	583–572	12 / 2	14.2	–	0.860	14.0	56.0	1.1203	0.23
45	957–937	1 / 0.1	50.0	0.450	0.500	0.2	0.8	1.3848	0.40
46	853–835	1 / 20	95.2	0.330	0.050	21.0	84.0	1.1248	0.50
47	1071–1041	6 / 4	40.0	0.230	0.600	10.0	40.0	1.4219	5.91
48	1126–1106	5 / 10	66.7	0.100	0.333	15.0	60.0	1.1353	0.56
49	634–626	8 / –	–	0.370	1.000	8.0	32.0	1.4807	6.41
50	830–776	5 / 6	54.5	0.200	0.550	11.0	44.0	1.1726	1.53
51	898–862	11 / 8	42.1	0.500	0.580	19.0	76.0	1.2052	1.83
52	286–262	0.1 / –	–	0.620	1.000	0.14	0.4	1.3235	3.24
53	638–621	10 / –	–	0.760	1.000	10.0	40.0	1.1464	0.48
54	712–664	4 / 1	20.0	0.400	0.800	3.5	20.0	1.1170	0.58
55	727–664	4 / 6	60.0	0.180	0.400	7.0	40.0	1.1333	0.73
56	1586–1570	10 / –	–	0.370	1.000	10.0	40.0	1.2098	1.40
57	730–1722	9 / –	–	0.250	1.000	9.0	36.0	1.1641	0.80
58	516–1498	1 / –	–	0.440	1.000	7.0	28.0	1.3602	5.27
59	585–550	0 / –	–	0.140	1.000	6.0	24.0	1.1399	0.93
60	637–610	0 / –	–	0.260	1.000	0.1	0.4	1.2105	1.51
61	917–886	3 / 8	72.7	–	0.270	7.7	44.0	1.4213	5.79
62	891–888	14 / –	–	1.000	1.000	14.0	56.0	1.1712	0.91
63	088–1060	7 / 7	50.0	0.180	0.500	14.0	56.0	1.3611	6.51
64	523–489	1 / –	–	0.680	1.000	8.05	28.0	1.2418	1.59
65	563–539	9 / –	–	0.370	1.000	9.0	36.0	1.1248	0.60
66	1120–1086	1 / –	–	0.260	1.000	0.5	28.0	1.2333	1.86
67	1767–1738	9 / –	–	0.410	1.000	9.0	36.0	1.2405	1.97
68	1553–1544	10 / –	–	0.440	1.000	10.0	40.0	1.2542	2.08
69	1674–1662	10 / –	–	0.170	1.000	10.0	40.0	1.2510	2.03
70	418–377	3 / –	–	0.440	1.000	3.0	12.0	1.1209	0.44
71	632–615	10 / –	–	0.240	1.000	16.0	40.0	1.1647	0.81
72	546–531	0.9 / –	–	0.200	1.000	0.9	3.6	1.1556	0.67
73	508–498	6 / –	14.3	0.300	0.857	7.0	28.0	1.1484	0.76
74	726–708	4 / –	–	0.710	1.000	4.0	16.0	1.2627	2.31
75	709–704	5 / –	–	–	1.000	3.5	20.0	1.2261	1.75
76	744–735	5 / –	–	0.770	1.000	5.0	20.0	1.3626	4.45
77	707–663	1 / –	–	0.160	1.000	1.0	4.0	1.1739	0.85
78	724–706	6.2 / 0.2	3.1	0.440	0.970	6.4	26.0	1.1307	0.29
79	1040–1015	3 / 0.3	9.1	-	0.900	3.8	13.0	1.1203	0.37
80	607–537	8.2 / 8.4	50.6	0.210	0.500	11.8	66.4	1.1294	0.37
81	420–363	8.4 / 1.2	14.3	0.720	0.760	9.6	38.4	1.1144	0.24

cont. Table 1/cd. Tabela 1

No of well	Screen	Oil / water production rate	Water cut (watering degree), X_3 [%]	The degree of immersion of pipes of the 1st row in the screen, X_4	Oil content in production, X_5	Flow rate ascending the production string, 10^{-2} m/sec, X_6	Upflow speed for 1st row of lifting pipes, 10^{-2} m/sec, X_7	Curvature factor, X_8	Specific volume of sand plug [m^3 per day]
82	437–362	4.5 / 1.1	19.6	–	0.80	5.6	22.4	1.1183	0.30
83	763–697	4.0 / 11.8	74.7	–	0.25	15.8	63.2	1.1229	0.27
84	413–405	0.4 / 0.1	20.0	0.36	0.80	0.5	2.0	1.1216	0.85
85	696–672	1.4 / 10,0	47.7	0.42	0.52	15.3	91.2	1.1569	1.09
86	724–686	9.7 / 2.1	17.8	–	0.82	8.3	47.2	1.2418	2.19
87	955–894	5.8 / 2.2	27.5	0.44	0.72	8.0	32.0	1.1229	0.27
88	812–805	4.0 / 1.7	25.4	–	0.74	4.0	22.8	1.1360	0.67
89	815–722	2.0 / 8.0	80.0	–	0.20	10.0	40.0	1.1210	0.64
90	913–903	14.3 / 2.5	14.9	–	0.85	11.8	67.2	1.1281	0.15
91	1054–1007	7 / 3	30.0	0.76	0.70	10.0	40.0	1.3965	6.43
92	585–556	8.0 / 20.0	71.4	0.21	0.29	19.6	122.0	1.1379	0.80
93	515–507	2.0 / 3.0	60.0	0.36	0.40	5.0	20.0	1.2072	2.36
94	477–462	4.0 / 14.0	77.8	0.20	0.22	18.0	72.0	1.1503	1.19
95	718–699	7 / 4	36.4	0.53	0.64	11.0	44.0	1.2333	2.36
96	1089–1075	7 / 17.0	70.8	–	0.29	24.0	96.0	1.3814	8.20
97	1406–1399	4.0 / 11.0	73.3	0.14	0.27	15.0	60.0	1.1262	0.72
98	433–421	4.0 / 2.0	33.3	0.75	0.67	6.0	24.0	1.1092	0.16
99	738–724	6.0 / 1.0	14.2	0.36	0,86	7.0	28.0	1.1360	0.47
100	800–730	2.5 / 0.5	16.7	–	0.83	3.5	12.0	1.1614	2.49
101	437–455	2 / –	–	–	1.00	2.0	8.0	1.1366	6.38
102	497–459	2 / 1	33.3	–	0.27	3.0	12.0	1.1497	1.28
103	472–454	1.5 / –	–	–	1.00	1.5	6.0	1.1922	1.23
104	743–714	3.0 / 1.5	33.3	–	0.67	3.2	18.0	1.1719	2.95
105	817–771	3.0 / 0.5	14.3	–	0.86	2.4	14.0	1.1268	1.96
106	543–498	2 / 1	33.3	–	0.67	2.1	12.0	1.1137	0.23
107	414–369	2 / 1	33.3	–	0.67	2.1	12.0	1.1163	0.27
108	629–591	6 / 2	25.0	–	0.75	5.6	32.0	1.1967	1.69
109	780–765	2 / 1	33.3	–	0.67	2.1	12.0	1.1608	1.25
110	724–681	3 / 0.5	14.3	–	0.86	2.4	14.0	1.1706	1,11
111	915–884	3 / 2	40.0	–	0.60	3.5	20.0	1.1170	0.48
112	575–533	5 / 5	50.0	–	0.50	7.0	40.0	1.1843	1.71
113	579–539	0.5 / 2.5	83.0	–	0.17	2.1	12.0	1.1020	0.19
114	563–524	2.0 / 0.5	20.0	–	0.80	1.8	10.0	1.1595	1.13
115	357–321	3.0 / 0.5	14.3	–	0.86	2.4	14.0	1.1706	1.15
116	367–321	2.5 / 1.0	28.6	–	0.71	2.4	14.0	1.1444	0.90
117	744–712	3.5 / 0.5	12.5	–	0.87	4.0	16.0	1.1412	0.65
118	418–360	2.0 / 0.5	14.3	–	0.86	2.5	10.0	1.1392	0.62
119	243–191	2.0 / –	–	–	1.00	2.0	8.0	1.1235	0.18
120	316–267	2.0 / 1.0	33.3	0.63	0.67	3.0	12.0	1.1209	0.34
121	612–578	4.0 / 2.0	33.3	–	0.67	4.2	24.0	1.2242	2.22
122	610–589	4.0 / 6.0	60.0	–	0.40	7.0	40.0	1.1719	1.12

cont. Table 1/cd. Tabela 1

No of well	Screen	Oil / water production rate	Water cut (watering degree), X_3 [%]	The degree of immersion of pipes of the 1st row in the screen, X_4	Oil content in production, X_5	Flow rate ascending the production string, 10^{-2} m/sec, X_6	Upflow speed for 1st row of lifting pipes, 10^{-2} m/sec, X_7	Curvature factor, X_8	Specific volume of sand plug [m^3 per day]
123	574–557	3.0 / 7.0	70.0	–	0.30	7.0	40.0	1.1412	0.75
124	383–370	2.0 / 1.5	42.9	–	0.57	3.5	14.0	1.1275	0.64
125	444–411	2.5 / 0.5	16.7	–	0.83	2.1	12.0	1.1163	0.27
126	251–219	4.0 / 1.0	20.0	–	0.83	2.1	12.0	1.1111	0.19
127	579–569	2.5 / 1.0	27.1	–	0.73	2.4	2.4	1.1216	0.65
128	556–530	2.0 / 1.0	33.3	–	0.67	2.1	12.0	1.1111	0.19
129	428–385	2.5 / 0.5	16.7	–	0.83	2.1	12.0	1.1190	0.21
130	515–491	2.0 / 3.0	60.0	–	0.40	3.5	20.0	1.1111	0.29
131	433–424	4.0 / –	–	–	1.00	4.0	16.0	1.1229	0.57
132	507–490	5.0 / 2.0	28.6	–	0.71	7.0	28.0	1.100	0.17
133	909–869	3.0 / 0.5	14.3	–	0.86	2.4	14.0	1.1229	0.67
134	796–763	1.5 / 0.5	25.0	–	0.75	2.0	12.0	1.1484	0.86
135	992–950	3.0 / 2.0	40.0	–	0.60	3.5	20.0	1.1085	2.08
136	980–936	20 / 1.0	33.3	–	0.67	2.1	12.0	1.1000	0.22
137	989–959	4.0 / 1.0	20.0	–	0.80	3.5	20.0	1.1294	0.47
138	223–188	2.0 / 6.0	75.0	0.34	0.25	5.6	32.0	1.1500	0.17
139	472–468	0.5 / 0.5	90.8	–	0.10	5.5	22.0	1.1004	1.21
140	566–535	7.0 / 2.0	22.2	–	1.78	9.0	36.0	1.1248	0.46
141	636–624	1.0 / 1.0	50.0	0.33	0.50	1.4	8.0	1.1118	0.63
142	519–499	7.0 / 3.0	30.0	0.55	0.70	7.0	40.0	1.1771	1.04
143	520–488	3.0 / 1.0	25.0	–	0.75	4.0	16.0	1.1196	0.22
144	338–335	3,0 / 2.0	40.0	–	0.60	5.0	20.0	1.1196	0.30
145	276–247	5.0 / 1.0	16.7	0.24	0.83	6.0	24.0	1.1248	0.46
146	438–428	6.5 / 7.0	51.9	0.20	0.48	13.5	54.0	1.1582	1.11

Note: The numbers of wells in the table are conditional

models as a support function. The purpose of the MGAA is to obtain the result of a complete enumeration of equations by the selection criterion, and not the result of applying the least squares method (regression analysis) (Ivakhnenko et al., 1976). MGAA belongs to a group of methods based on the mathematical processing of historical data. The fundamental difference between MGAA and regression analysis is the achievement of a minimum of a reasonably chosen selection criterion, that is, minimization of the variance and maximum unbiasedness of the model describing the process. The model that is found according to the unbiasedness criterion is optimal for multiple system differential prediction, the idea of which is to repeatedly use the exact physical model (Ivakhnenko, 1976).

The test sequence is used in the MGAA to select the number of terms and the degree of the regression equation.

The process of searching for the minimum of the specified selection criterion is implemented by processing the initial information in a computer program (patented by the National Academy of Sciences of Ukraine). The essence of the process is to enter an array of initial information. It is also important that the nature of the dependency is obtained from experts (field specialists and engineers), then the program processes the data step by step and produces the equations for the dependence of the characteristic under consideration on one or another criterion (numerical dependence coefficients, which are called normalizing coefficients, are obtained as a result of data processing by the program algorithms).

As a result, a model of optimal complexity is synthesized for a number of experimental points (based on field data).

Specificity only involves the choice of criteria that correspond to the condition of the problem under consideration (Ivakhnenko, 1976).

Then equation (1) takes the following form:

$$Y = 16.125 \cdot 10^{-4} X_1^3 - 0.319\sqrt[3]{X_2} + \\ + 0.238\sqrt[3]{X_3} + 15.943 X_8 \quad (2)$$

Table 2. Partial dependencies of the factors affecting plug formation

Tabela 2. Częściowe zależności czynników mających wpływ na kolmatację w odwiertach

No.	Factors affecting plug formation at the bottom of wells	Designation of factors	Equations
1.	Oil production rate	X_1	$Y = 1.06 + 0.285 \cdot 10^{-4} X_1^3$
2.	Water production rate	X_2	$Y = 1.37 + 0.276\sqrt[3]{X_2}$
3.	Water cut (watering degree)	X_3	$Y = 1.49 + 0.159\sqrt{X_3}$
4.	The degree of immersion of pipes of the 1st row in the screen	X_4	$Y = 0.978 + 0.377\sqrt{X_4}$
5.	Oil content in production	X_5	$Y = 0.901 + 0.473 X_5^4$
6.	Flow rate ascending the production string	X_6	$Y = 1.04 + 0.641 10^{-3} \cdot X_6^2$
7.	Upflow speed for the 1st row of lifting pipes	X_7	$Y = 1.08 + 0.207 \cdot (1/X_7^2)$
8.	Wellbore curvature factor	X_8	$Y = -13.8 + 14.0 X_8$

As can be seen, the specific volume of the washed sand plug is influenced by the oil and water flow rate, the water cut of the product and wellbore curvature factor. Moreover, the influence of the coefficient of curvature of the wellbore is greater than the influence of the other factors. To predict the possibility of plugging, Pattern Recognition Methods (PRM) can be used. One of such methods, which is widely used in problems of alternative decision making, with a large number of controllable and uncontrollable factors affecting the process, is a sequential diagnostic procedure (Mirzajanzade and Stepanova, 1977; Mirzajanzade, 1986; Mirzajanzade et al., 1997).

When using this method, all wells are first divided into two groups: A and B, depending on the parameter characterizing the efficiency of the process.

In this case, the parameter characterizing the efficiency of the process is the specific volume of the sand plug (*Y*).

Numerous experiments and studies in the field of plug formation in production oil wells show that when the value of the specific volume of the washed sand plug is below 0.01 m³ per day, there is no significant change in the technological parameters of well operation. When (*Y*) is greater than 0.01 m³, a noticeable decrease in the flow rate and deterioration of other technological parameters occur.

Based on this, the first group (*group A*) included wells where $Y < 0.01$, and the second group (*group B*) included wells where $Y > 0.01$.

The diagnostic coefficients and informativity of signs in each group are then calculated. The values of the features are presented as an ordered series, which is divided into recommended 8–12 intervals.

The frequency of hitting wells from groups *A* and *B* in each interval is determined. To minimize the influence of interval boundaries on the results, weighted average (smoothed) frequencies are determined in each interval by calculating the weighted sliding average.

Next, diagnostic coefficients (DC) are calculated according to the formula:

$$DC = 10 \cdot \lg(X_A / X_B) \quad (3)$$

The informativity of features in each interval is determined by the formula:

$$I\left(X_i^3\right) = DC\left(X_i^3\right)\frac{1}{2}\left[P\left(\frac{X_i^3}{A}\right) - P\left(\frac{X_i^3}{B}\right)\right] \quad (4)$$

where *DC* is the diagnostic coefficient of the *i*-th range of the 3rd sign; $P(X_i^3/A)$ and $P(X_i^3/B)$ – probability (smoothed particularity) of getting into group *A* and *B* of the 1st range of the 3rd feature; $P(X_i^3/A) - X_A$ and $P(X_i^3/B) - X_B$.

The informativity of a given feature is calculated by summing the information content of its ranges:

$$I\left(X_3\right) = \sum I\left(X_i^3\right) \quad (5)$$

As can be seen, the wellbore curvature coefficient is an informative feature, which coincides with the result of the correlation analysis (Mirzajanzade et al., 2003).

To predict the need for one or another measure to control plugging in wells, the sum of diagnostic coefficients for each well was also calculated.

By constructing a graph of the distribution of the number of wells over the intervals of change in the sum of diagnostic coefficients ($\sum DC$), it is possible to set the threshold value of these sums.

Figure 1 shows a graph of the distribution of the number of plug-forming wells over the intervals of change in diagnostic sums. As can be seen, in zone *A*, where the sum of diagnostic coefficients is between 4–12, there are mainly wells with a specific volume of washed sand plug less than 0.01 m³ per day.

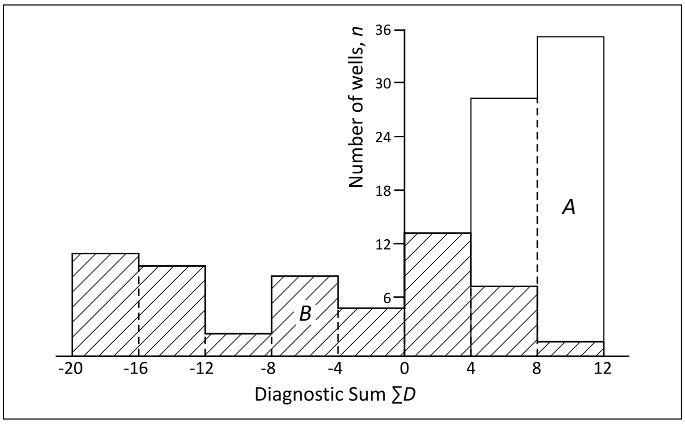

Figure 1. Graph of the distribution of the number of plug-forming wells by intervals of change in diagnostic sums

Rysunek 1. Wykres zależności liczby odwiertów ulegających kolmatacji względem przedziałów zmian sum diagnostycznych

Conclusions

1. If, according to the initial data, the sum of diagnostic coefficients falls within 4–12, then there is no need for plugging measures, in all other cases it is necessary to provide for geological and technical measures to prevent sand plug formation.
2. It was determined that the coefficient of curvature of the wellbore has a greater impact on the process of plug formation at the bottomhole, and therefore it is necessary to implement technological measures to reduce the frequency of plug formation, taking into account the degree of inclination of the well.
3. Measures should be taken to suppress the influence of the inclination of wells on plugging, taking into account the hydraulic characteristics of the upward flow of the sand-liquid mixture along the inclined wellbore.
4. According to the initial field information, MGAA allows to identify the main factors influencing the process of plug formation in directional wells. Based on the diagnostic criterion and the resulting model, which is characterized by minimal dispersion, it seems possible to classify the wells to one or the other group, resulting in a reasonable decision to implement geological and technological measures to control or eliminate the formation of a sand plug in the wellbore, which, in turn, has a positive effect on the mining process.

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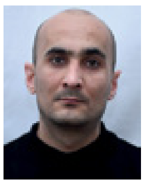

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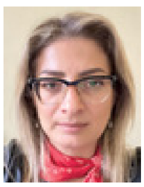

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