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Research on Water Sensitivity and Velocity Sensitivity of Loose Sandstone Reservoir in China Offshore Oilfield

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Abstract

Aiming at the development characteristics of Bohai P oilfield, formation mechanism of reservoir damage was analyzed by mines of mineral composition, micro-pore structure, and seepage mechanism. Microscopic petrological observations and laboratory core experiments show that the content of clay minerals such as the Imon mixed layer and kaolinite is high with high porosity and good pore roar structure; the water sensitivity is medium to strong, The lower the salinity of injected water, the greater the drop in core permeability; the velocity-sensitive damage is strong, and permeability increases with the increase in flow velocity, and a large number of particles are observed in the produced fluid under the microscope. Aiming at the contradiction of velocity sensitivity between core permeability increase and the permeability decrease near the wellbore, the velocity sensitivity seepage model of "long-distance migration and blockage near the well" is proposed, and the permeability and formation distribution formula are deduced. The calculated value is close to the test value of actual pressure recovery test. The research results of water sensitivity and velocity sensitivity provide important guidance for Bohai P oilfield to improve production and absorption capacity and reservoir protection.

Keywords

Reservoir Damage, Water Sensitivity, Velocity Sensitivity, Loose Sandstone, Seepage Mechanism, Clay Minerals

1. Introduction

Bohai P oilfield is located in the southeast of Bohai Bay. The oil-bearing layers are the Neogene Guantao Formation and the lower part of Minghuazhen For-

mation, which belong to shallow-water braided river delta deposits and meandering river deposits. The lithology of the reservoirs is fine, medium-fine and gravel-bearing medium-coarse sandstones. The rock is unconsolidated, argillaceous-cemented with relatively high clay minerals, 7% to 79% illite-smectite, and 6% to 63% Kaolinite. The reservoirs are characterized as high porosity at 25% - 32% and high permeability at 400 mD - 2000 mD. P oilfield has been developing with sea-water injection and is currently producing at high water cut stage. Some oil producers and water injectors have been encountering poorer performances showing as low-productivity for producers and low-injectivity for water injection wells, which impaired the effectiveness of oilfield development and asset economics. Currently, there're two challenges: 1) No/Low injection: the water injection volumes even at the high wellhead injection pressures are still too low to provide sufficient pressure support for the development of the field; 2) No/Low production: at present, most of the reservoirs show reasonably sufficient formation energy overall, but the well/field has been exhibiting decrease both for liquid production and bottom-hole flowing pressure, which therefore led to the high decline in oil production at well/fieldwide. With these two challenges, the damage mechanism to such reservoirs and its associated preventive measures are studied which include characteristics of the pore structure, mineral contents and practical production offtake rate, etc., the research on such reservoir damage at home and abroad mainly focuses on core experiments in laboratory and field site statistics [1]-[6], and there are few studies on its intrinsic seepage mechanism, especially the velocity-sensitive damage at the fieldwide scale is less reported.

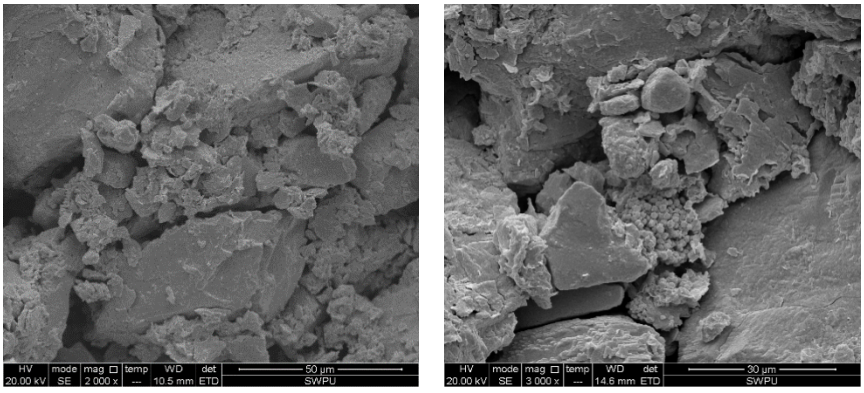
2. Microscopic Petrology and Pore-Throat Characteristics

2.1. Micro Petrological Features

According to the X-ray rock composition analysis, the mineral composition of the reservoir is mainly quartz, feldspar and cuttings at 40%, 25%, and 20% respectively. The identification of the cast thin section shows that the rock is loose, muddy-cemented, and the content of interstitial materials is high, including particles such as clay and silt. Further analysis of the clay content by X-ray diffraction shows that the particle size is less than 1 μm, the content of kaolinite is 28%, green mudstone is 12%, the illite is 16%, and illite/smectite interlayer minerals are the highest at an average of 43%. Scanning electron microscope shows that some of the minerals in the mixed layer of I/O cover the surface of rock particles, or form bridges between filling particles (**Figure 1**), causing potential damages of water-sensitivity and velocity-sensitivity to the reservoir [7] [8] [9] [10] [11].

2.2. Pore Structure Features

Cast thin sections and scanning electron microscopy show that the reservoir has well-developed pores and good connectivity. The pore space is dominated by primary intergranular pores, followed by secondary pores such as intragranular



(a) (b)

Figure 1. Occurrence of reservoir clay minerals in Bohai P oilfield ((a): Illite-smectite mixed layer filling intergranular pores; (b): Kaolinite filling intergranular pores).

dissolved pores. According to statistics, the primary intergranular pores account for more than 95% of the total pores. The pore-throat is dominated by sheet-like throat, followed by contracted and point-throat. Core mercury intrusion data show that the capillary pressure curve of the reservoir is characterized as roughness with the displacement pressure of 0.013 - 0.625 MPa, the average pore throat radius of 2.513 - 11.786 μm, and the mercury displacement efficiency of 4.7% - 33.6%, which exhibits high porosity, high permeability and better pore structure characteristics (**Table 1**).

3. Experimental Procedure and Discussion on Results

3.1. Water Sensitivity Test

The water/salinity sensitivity of oil layers refers to the phenomenon that the change of fluid salinity causes the swelling, dispersion and migration of clay, which changes the seepage channel and leads to the change of the permeability of the reservoir rock [12]. Referring to the oil and gas industry standard (China) SY/T5358-2010 "Formation Damage Evaluation by Flow Test", the primary experimental steps include:

1) The experimental cores were washed with oil until water-wetted, dried, and the air permeability was measured;

2) Saturate the core with simulated formation water and soak it for more than 24 hours;

3) Put the rock sample into the core holder, add the confining pressure, and keep the effective stress of the core at 2 MPa;

4) Under the simulated reservoir temperature conditions, formation water is used to test core permeability K_{w0}; 10 - 15 times the pore volume of 75% formation-water-salinity is used to displace cores and measure its permeability K_{w1}, and soak in this brine for 12 hours; then performing the same process with 50% formation-water-salinity, 25% formation-water and deionized-water (distilled water) salinity, and the permeability K_{w2}, K_{w3} and K_{w4} are measured respectively.

Table 1. Mercury parameters of reservoir layers in Bohai P oilfield.

sample	displacement pressure MPa	maximum pore-throat radius μm	average throat radius μm	homogeneity coefficient	mercury displacement efficiency %	maximum mercury saturation %
1-004B	0.007	105.01	16.91	0.17	10.8	84.9
1-007B	0.020	37.03	10.54	0.29	11.6	79.5
1-013B	0.024	30.44	11.57	0.37	6.8	89.4
1-014B	0.024	30.44	12.65	0.42	7.1	89.6
1-015B	0.031	23.67	8.82	0.38	4.7	80.1
1-017B	0.014	53.13	16.14	0.30	5.5	83.4
2-002B	0.024	30.42	9.89	0.32	8.2	76.2
2-008B	0.031	23.67	7.64	0.32	6.7	89.3
2-010B	0.076	9.703	1.86	0.19	33.6	83.7

The results show that the water-rock sensitivity of the 4 cores is medium to strong. As shown in Table 2, the core 1-015A with the highest permeability is relatively weak water-sensitive, and the other 3 cores are relatively strong. The critical salinity of 1-015A core is 15,000 ppm (75% formation water salinity), and the other three are 20,000 ppm *i.e.*, the formation water salinity.

The above experimental results indicated that the more the injected water salinity is closer to that of the formation water, the less water-sensitive the core is. Therefore, the decrease of permeability near the wellbore caused by the swelling of clay minerals in water is the main reason for the "No/Low-injection" of the P oilfield. After adding the clay anti-swelling additives to the injected water, the water injectivity index is greatly increased [13] [14], and the expected fieldwide water injection volume with lower injection pressure is achieved (Table 3).

3.2. Velocity Sensitivity Test

The velocity-sensitivity of oil and gas reservoir is the phenomenon that the particles in the reservoir move and block at some pore throats, which results in the change of the permeability of the reservoir rock [15]. Experimental procedure:

1) The experimental cores were washed with oil until water-wetted, dried, and the air permeability was measured;

2) Saturate the core with simulated formation water and soak it for more than 24 hours;

3) Put the rock sample into the core holder, add the confining pressure, and keep the effective stress of the core at 2 MPa;

4) The simulated formation water was injected into the core at the rates of 0.25 mL/min, 0.5 mL/min, 0.75 mL/min, 1.0 mL/min, 2.0 mL/min, 3.0 mL/min, 4.0 mL/min, 5.0 mL/min and 6.0 mL/min respectively, the displacement pressure difference under each displacement velocity was recorded;

Table 2. Evaluation results of water sensitivity experiment.

core	original permeability K_i, mD	K, mD					Water sensitivity damage %	assessment
		formation water	3/4 formation water	1/2 formation water	1/4 formation water	deionized water		
1-015A	511.9	511.9	449.1	350.4	308.1	259.4	49.3	weak
2-015A	50.0	50.0	40.2	38.6	30.2	21.3	57.3	strong
1-003A	289.0	289.0	213.9	180.4	152.5	143.7	50.3	strong
2-010A	27.0	27.0	19.4	17.9	17.1	12.6	53.1	strong

Table 3. Water absorption capacity before and after anti-swelling in P oilfield.

well	Thickness m	before anti-swelling			after anti-swelling		
		wellhead pressure MPa	injection volume m^3/d	absorption index $m^3/(d·MPa·m)$	wellhead pressure MPa	injection volume m^3/d	absorption index $m^3/(d·MPa·m)$
A04ST2	60.2	4.65	791	2.83	4.93	997	3.36
E07	86.4	6.64	496	0.86	6.96	960	1.60
E55	39.1	6.42	438	1.74	6.62	858	3.31
E31	49.7	5.53	371	1.35	4.75	668	2.83
M05	70.4	4.89	113	0.33	3.86	173	0.64

5) Permeability K_n (n = 1, 2, 3, 4, …) at different displacement rates, the damage of the velocity-sensitivity is calculated.

During the experiment, filter paper was used at the core outlet to filter the produced fluid, and the formation particles were observed, and their sizes were measured (**Figure 2**). According to the experiment, the permeability increases with the increase of flow velocity, which is mainly due to the short in length of the experimental core—"End Effect", loose cementation and the flow of transportable particles out of the core. The microscopic observation of the produced fluid collected from the outlet of test core (**Figure 3**) shows that there are a lot of particles in the core during the displacement process.

4. Mechanism of Velocity-Sensitive Seepage Flow

According to the velocity-sensitive experiment, the permeability would increase against the higher flow velocity at the core scale, which is not consistent with the observation at the field site, the decreases both for the fluid production and permeability near the wellbore in P oilfield. In view of this phenomenon, a percolation model of "Long-distance migration and near wellbore plugging" of fine particles is put forward: The permeability and porosity of the p oilfield are high with relative good in the pore throat structure, but the cementation is loose, mineral particles such as kaolinite and illite-smectite mixed layer are easy to be

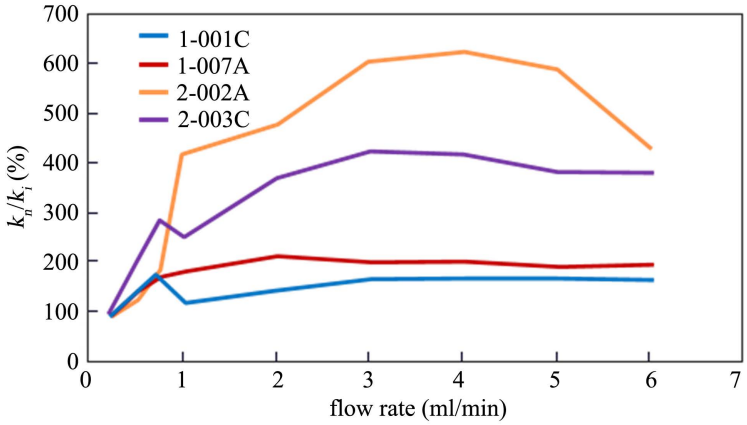


Figure 2. Core velocity sensitivity test results in P oilfield.

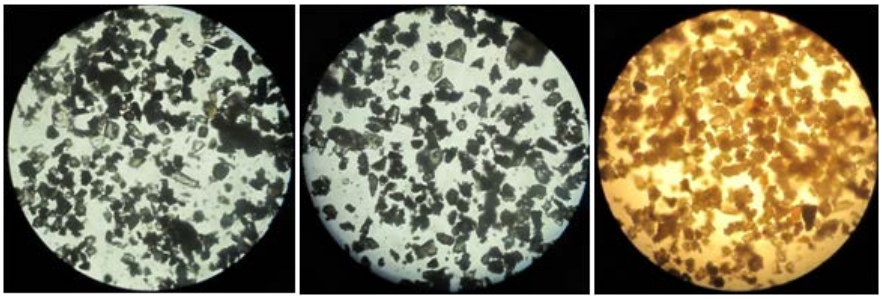


Figure 3. Particles produced at the core exit in P oilfield velocity-sensitive experiment.

washed down from the pore wall under the high flow rate of formation fluid [16]. Except for a few deposits in the pore throat, most of the particles which have a smaller size in radius than the pore throat are easily migrated to the area near the wellbore. For Directional (slanted) wells, the closer to the wellbore, the smaller the cross-sectional area of seepage flow and the larger the velocity of porous flow.

In order to quantitatively evaluate the effect of velocity-sensitivity, the relationship between seepage velocity and permeability is introduced, and the concept of blocking coefficient is introduced as well [17], and the following relationship is obtained:

$$K = K_i \cdot \left[\left(1 - 0.2\mathrm{e}^{-2.5\alpha_k}\right) \cdot \mathrm{e}^{-\alpha_k\left(\frac{v}{v_w}-1\right)} + 0.2\mathrm{e}^{-2.5\alpha_k} \right] \tag{1}$$

K is permeability, μm^2; K_i is the original permeability, μm^2; α_k is blocking coefficient; v_w is Percolation velocity at wellbore, m/d.

Under the condition of steady radial flow, the seepage velocity at the wellbore is assumed to be [18] [19]:

$$v = \frac{K}{\mu}\frac{\partial P}{\partial r} \tag{2}$$

μ is oil viscosity, mPa·s; $\partial P/\partial r$ is Pressure derivative, MPa/m.

The seepage velocity at any radius is:

$$v = \frac{K}{\mu}\frac{\partial P}{\partial r}\bigg|_{r_w} = \frac{Q}{2\pi h r_w} \tag{3}$$

r_w is wellbore radius, m; Q is daily production, m^3/d.

The difference of Formula 3 is obtained [20]:

$$v_{i+1} = \frac{K_{i+1}}{\mu}\frac{P_{i+1} - P_i}{\Delta r} \tag{4}$$

v_{i+1} is percolation velocity at any point in the formation, m/d; Δr is space step, m; K_{i+1} is the permeability of $i + 1$, m^2; P_{i+1} is pressure of $i + 1$, MPa; P_i is pressure of i, MPa.

Formula (4) can be transposed as:

$$P_{i+1} = P_i - \frac{V_{i+1} \cdot \mu \cdot \Delta r}{K_{i+1}} \tag{5}$$

Formula (5) can be used to iterate the seepage velocity and permeability, the formation pressure distribution and the formation damage caused by velocity-sensitivity can be obtained.

A directional well is assumed to have a wellbore radius of 0.2 m, a circular supply radius of 300 m, a boundary pressure of 12 MPa, a production thickness of 50 m, daily production of 500 m^3/d, a primary permeability of 1 μm^2, and a formation fluid volume factor of 1.05, the apparent viscosity of formation fluid is 5 mPa·s, and the distribution curves of formation permeability and formation pressure can be obtained when the plugging coefficients are 0.00, 0.01, 0.10 and 0.30 respectively (**Figure 4**).

As it can be seen from **Figure 3**, the more serious the velocity-sensitivity to the reservoir, *i.e.* the greater the plugging factor is, the more serious decreases in permeability near the sand face of the wellbore. When the bottom-hole flowing pressure drops down to the limit of ESP, the production of the directional well will be dominated by constant bottom-hole flowing pressure. With the particle accumulation of clay minerals, the daily production fluid will gradually decrease as a result of near wellbore plugging/blocking effect, that is, the phenomenon of "No/Low production" will occur.

In order to quantitatively evaluate the damage degree of reservoirs caused by velocity-sensitivity, pressure-buildup tests (PBU) were carried out in some directional wells of P oilfield during production phase, and the results are compared with the calculated values (**Table 4**). The blocking coefficient of

Table 4. Comparison of the PBU test and calculation result in Bohai P oilfield.

well	r_e	r_w	P_e	h	Q	K_i	μ_o	P_{wf}	α_k	K_{tested}	$K_{calculated}$
	m	m	MPa	m	m^3/d	μm^2	mPa·s	MPa	Dimensionless	μm^2	μm^2
A14ST4	260	0.15	11.6	30.0	172	854	5.8	5.5	0.38	89	67
A17ST3	280	0.15	11.4	41.1	190	748	5.3	5.0	0.46	34	46
E25ST1	300	0.20	12.8	27.3	225	940	2.9	5.1	0.69	7	34
E36ST1	290	0.20	12.5	40.6	440	697	6.8	5.9	0.03	209	129

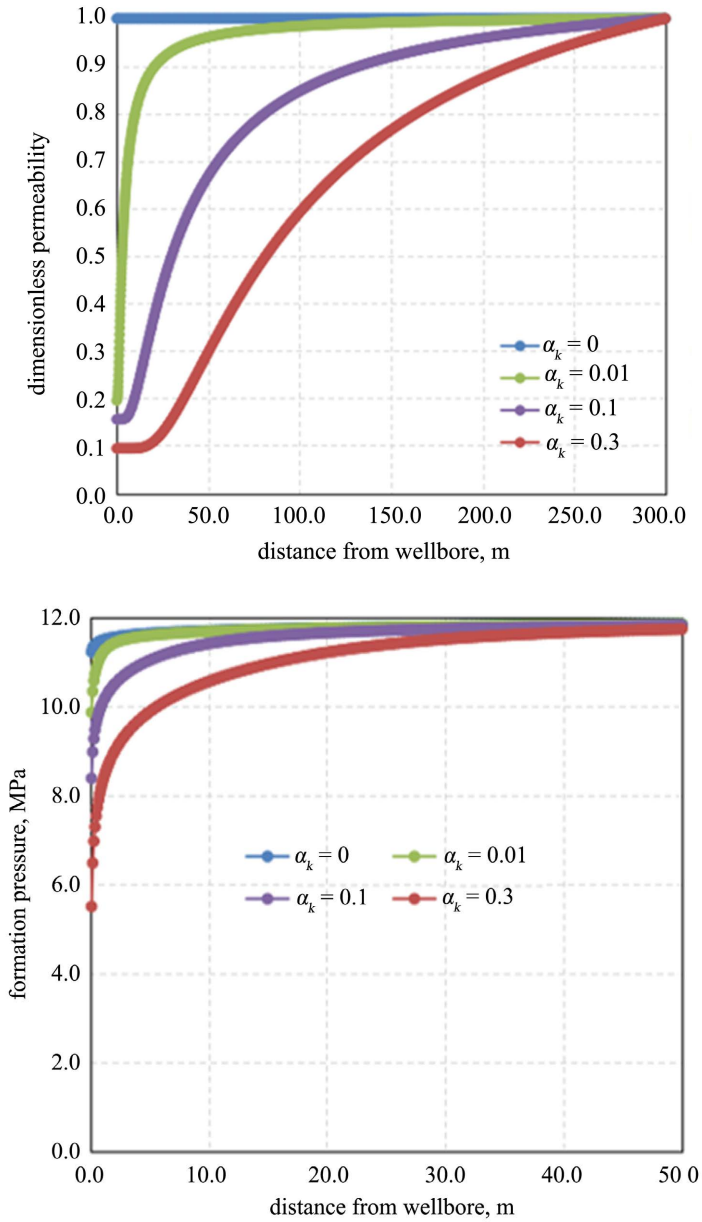


Figure 4. Formation permeability and pressure distribution under different plugging coefficients.

velocity-sensitivity is 0.03 - 0.69, the calculated permeability is close to the tested permeability.

5. Conclusions

1) Clay Minerals such as illite-smectite mixed layer and kaolinite in the reservoirs of the P oil field in Bohai Bay are high, which is easy to swell and plug up the pores when it is exposed to injected water. The reservoir pores are well developed and connected, and the clay particles with loose cementation are easy to move under high flow velocity, and this's the primary driver of the reservoir damage due to water/velocity sensitivities.

2) The sensitivity of water salinity is strong. The lower the salinity of injection water is, the more serious damage in rock permeability is; the velocity-sensitivity is strong too, and the reservoir permeability would be impaired against high off-take rates although the lab tests show the opposite observation.

3) In view of the contradiction between core-scale against well site observations, a velocity-sensitive seepage flow model of "long-distance migration and near-wellbore plugging" is proposed, and the formulas to calculate permeability and formation pressure are derived.

4) In order to sustain the expected production and injection capacity of P oilfield, it is suggested that anti-swelling measures should be carried out in injection wells to reduce water sensitivity damage to the reservoirs, and that plugging removal measures should be carried out regularly in production wells, moreover, reasonable pressure drawdown control for production wells should be maintained to better manage the velocity-sensitivity damage to the reservoirs.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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