Hindawi
Geofluids
Volume 2022, Article ID 7983330, 9 pages
https://doi.org/10.1155/2022/7983330

Research Article

Study on Reasonable Formation Pressure Maintenance Level for Middle-Deep Reservoirs in the Bohai Sea

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Received 11 April 2022; Revised 13 May 2022; Accepted 19 May 2022; Published 11 June 2022

Academic Editor: Shuyang Liu

Reasonable formation pressure maintenance level is significant to high-efficient development of oilfields. In order to study the effects of overlying strata pressure on permeability, oil-water phase permeability curve, and oil displacement efficiency, a physical simulation experiment is designed. Based on the experimental results and the oil-water phase flow theory, the production equation and the mathematical model of oil displacement efficiency considering stress sensitivity are established. And the productivity changes with pressure drop under different permeability are plotted. Then, the permeability coefficients calculated by quantitative characterization of stress sensitivity under different formation pressures are introduced into the numerical simulation model to quantitatively determine the reasonable formation pressure maintenance level of different reservoir properties. Experimental and theoretical studies show that the permeability decreases continuously with the increase in effective overlying strata pressure. In a low permeability reservoir, the more permeability decrease is caused by the increase in effective overlying strata pressure. When reservoir pressure is restored by water injection, the permeability loss is irreversible. With the increase in effective overlying strata pressure, the producer productivity decreases obviously, and the effective seepage capacity and oil displacement efficiency decrease. For reservoirs with permeability below 100 mD and high stress sensitivity, high formation pressure level should be maintained. For reservoirs with permeability of more than 300 mD, lower formation pressure is acceptable in the initial stage. The results are consistent with the actual production characteristics, which effectively guide the establishing of reasonable oilfield development strategy. It has important guiding significance to the oilfield development plans and development of the middle-deep oilfields.

1. Introduction

Pressure is the soul of the oilfield development process. Reasonable formation pressure maintenance is the key to the entire pressure system [1–4]. It not only determines the injection pressure and formation pressure of the injector but also restricts the flow conditions of the producer. Maintaining a reasonable formation pressure is the foundation for achieving stable production in the oilfield. The production pressure difference of the producer is reduced with a low formation pressure, while the seepage capacity is reduced, the energy is insufficient, the productivity of the producer is reduced, and the production cannot meet the demand. However, the high requirements for wellhead equipment will greatly increase the cost while the formation pressure is too high. At the same time, the contradiction between the horizontal and vertical of the oilfield is aggravating. The predecessors [5–9] used an empirical formula method, minimum flow pressure method, reasonable injection-production pressure system method, crude oil loss function method, material balance method, injection-production balance method, and other methods to study the reasonable maintenance level of formation pressure and get some remarkable achievement. But there is no research considering the pressure-sensitive effect caused by the formation pressure drop yet. It is proposed for the first time that the influence of the pressure-

Table 1: Table of core parameters.

Well	Layer	Core depth (m)	Core length (cm)	Core diameter (cm)	Gas permeability (mD)
3	E_2s_3	2569.40	5.58	2.54	10
3	E_2s_3	2563.40	5.52	2.54	30
5	E_2s_3	2491.5	6.48	2.54	100
2	E_2s_3	2554.26	5.37	2.54	300
2	E_2s_3	2454.26	5.37	2.54	1000

sensitive effect is caused by the decrease in formation pressure through physical simulation experiments, reservoir engineering methods, and numerical simulation technology. And then, determine pressure maintenance level under different reservoir conditions.

2. The Impact of Formation Pressure Maintenance Level on Productivity

When the reservoir is not developed, the reservoir rock is in a state of static equilibrium under the combined action of the pressure of the overlying strata, the pore fluid pressure, and the supporting force of the rock skeleton. During the reservoir developing, as the fluid is produced, the pore fluid pressure gradually decreases. With the pressure of the overlying strata unchanged, the supporting force of the rock skeleton continues to increase and the pore throats and microcracks of the rock are compressed, which lead to changing the physical properties of rocks [10–13]. Therefore, the influence of rock stress sensitivity should be considered in the development process.

2.1. Stress Sensitivity Test. The basic principle of the stress sensitivity test is to simulate the effective overlying strata pressure of the oil and gas reservoir [14–16]. Pressurize the rock core to a certain value andthen gradually reduce the pressure to return to the initial overburden pressure. Study the non-steady state of permeability changing with the overburden pressure process [17, 18]. Approximately take the difference between the overlying strata pressure and the pressure of the pore fluid in the rock as the effective overburden pressure, use the confining pressure to simulate the pressure of the overlying formation, and increase the confining pressure to simulate the continuous decrease in the pore pressure of the formation and cause the effective pressure of the rock skeleton to gradually increase.

(1) Number of cores and basic conditions: select cores with a permeability of 10~1000 mD (Table 1), which can better reflect 5 sets of cores with different physical properties for experiment

(2) The conditions of the gas used in the experiment: this experiment uses nitrogen for displacement, the displacement pressure is set to 2 MPa, the temperature is 20°C (room temperature), and the nitrogen viscosity is 0.018 mPa·s

(3) Experimental instruments: the main instruments used in this experimental design are nitrogen bottles, core holders, hand pumps, gasflowmeters, and pressure gauges. The design drawing of the experimental instrument is shown in Figure 1, and the physical photo of the experimental instrument is shown in Figure 2

Experimental process: (1) put the measuring core in the core holder, adopt the gas permeability method, and set the driving pressure to 2 MPa; (2) after the gas flowmeter reading is stable, change the effective stress of the core through the confining pressure pump to simulate formation stress-sensitive environment, and record the experimental data after the gas flowmeter reading is stable; (3) continuously increase the confining pressure with a change of 2 MPa, record the flowmeter reading, and stop after the confining pressure rises to 25 MPa. Then, enter the pressure reduction process.Decrease the confining pressure with a change of2MPa and record the gas flowmeter reading. Repeat the process of lifting andlowering pressure three times to reduce experimental error; (4) after completing three times of lifting and lowering pressure process, relieve the confining pressure pump, turn off the air pump, remove the core holder, replace the core, and repeat the above process.

2.2. Analysis and Quantitative Characterization of Stress-Sensitive Experiment Results. The experimental research results show that with the increase in the effective overburden pressure, the permeability continues to decrease, and the lower the core permeability, the greater the drop in permeability caused by the increase in the effective overburden pressure (Figure 3). Generally speaking, the changes can be divided into two stages. In the first stage, the effective overburden pressure is less than 10 MPa, and the decline is relatively large. Due to the overburden pressure, the rock skeleton is deformed, resulting in a rapid decrease in permeability. In the second stage, the overlying pressure is 10-25 MPa, and the decrease is relatively slow. With the increase in the overlying pressure, the pore structure changes very little, and the drop in permeability is not obvious.

As the effective overburden pressure decreases, the permeability gradually recovers. The lower the core permeability, the greater the permeability loss. Therefore, even if the reservoir pressure is restored by water injection during oilfield development, the permeability can only partially recover, and the permeability loss is irreversible.

Experimental results show that cores with different permeability levels are stress-sensitive, and the difference in

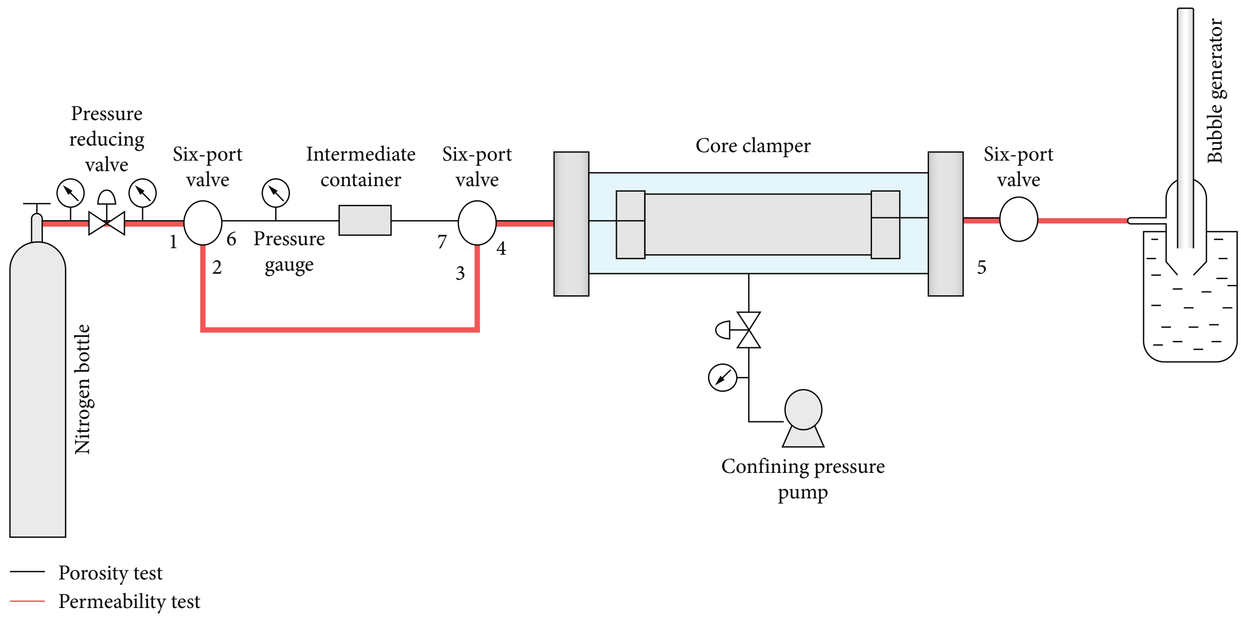

Figure 1: Layout of the experimental apparatus.

Figure 2: Object pictures of experimental instruments.

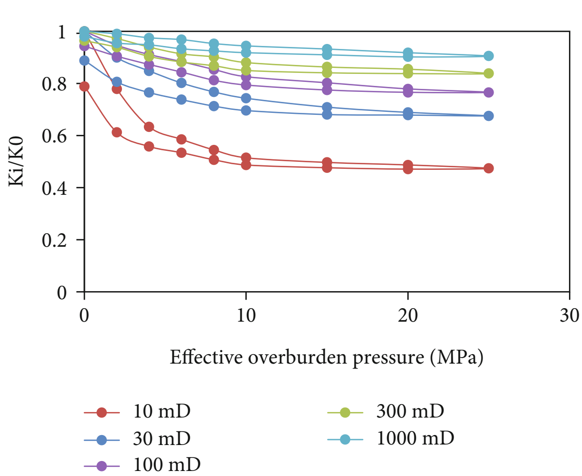

Figure 3: The variation of permeability of different core permeability with effective overburden pressure.

permeability determines the degree of stress sensitivity. As a whole, the permeability under different effective overburden pressures has a power relationship with the effective overburden pressure:

$$\frac{K_i}{K_0} = a \times \sigma^{-s}. \quad (1)$$

In the formula, K_0 is the initial permeability (mD), K_i is the permeability under effective overburden pressure (mD), σ is the effective overburden pressure (MPa), s is the stress sensitivity coefficient, and a is the regression coefficient.

In order to quantitatively characterize the stress sensitivity under different permeability conditions, a quantitative relationship between the stress sensitivity coefficients regressed from 5 sets of data and the initial permeability of the core is established (Figure 4).

Considering that the regression coefficient a is around 1, the quantitative expression of reservoir stress sensitivity is simplified as

$$K_i = K_0 \times \sigma^{-\left(0.4237 \times K_0^{-0.352}\right)}. \quad (2)$$

According to the similarity between the increase in effective overburden pressure (increasing confining pressure) and the actual pore pressure drop in the oilfield, the relationship between the permeability and the pressure in the actual production process of the oilfield can be further obtained:

$$K_i = K_0 \times (P_e - P_i)^{-\left(0.4237 \times K_0^{-0.352}\right)}. \quad (3)$$

In the formula, P_e is the original formation pressure (MPa) and P_i is the current formation pressure (MPa).

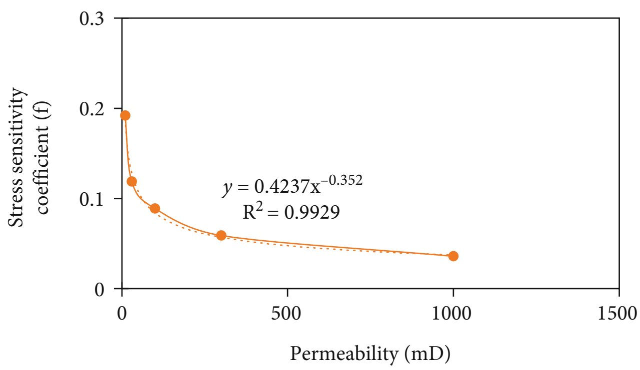

Figure 4: Distribution of stress sensitivity coefficient under different permeability.

Further establish the productivity equation considering the stress sensitivity. The producer plane radial stable seepage equation [19] is formula (4).

$$Q = \frac{2\pi \bullet K_i \bullet h}{\mu_o \bullet B \bullet (\ln (r_e/r_w) + S)} \bullet \Delta P. \quad (4)$$

In the formula, Q is the production (m^3/d), h is the reservoir thickness (m), μ_o is the oil viscosity, mPa·s, B is the oil volume coefficient, r_e is the supply radius (m), r_w is the well radius (m), ΔP is the production pressure differential (MPa), and S is the skin factors.

Considering the stress sensitivity caused by the drop in formation pressure during the production process of a producer, substituting formula (3) into (4) .

$$Q = \frac{2\pi \bullet h}{\mu \bullet B \bullet (\ln (r_e/r_w) + S)} \times K_0 \times (P_e - P_i)^{-\left(0.4237 \times K_0^{-0.352}\right)} \times \Delta P. \quad (5)$$

Incorporate the basic parameters of the oilfield into formula (5), and plot the change of productivity with pressure drop under different permeability of the oilfield (Figure 5). It can be seen that the formation pressure drop has a greater impact on the productivity. At the initial stage of the formation pressuredrop, the large productivity drop is mainly due to the deformation of the rockskeleton and even closure of the pore throats, resulting in a rapid decrease inpermeability. When the pressure of a low-permeability reservoir drops by 5 MPa, the productivity loss exceeds 20%. In the medium permeability reservoir, when thepressure drops by 10MPa, the productivity loss exceeds 10%.And when the pressure in the high-permeability reservoir drops by 15 MPa, the productivity loss exceeds 10%. In general, as the formation pressure decreases, the productivity gradually decreases. The lower the permeability, the greater the productivity loss. The reasonable pressure levels should be determinedaccording to the different physical properties of reservoirs.

In order to ensure the long-term stable development of the oilfield, the maximum pressure drop of middle-deep reservoirs in the Bohai Sea is generally controlled below 5 MPa for reservoirs with permeability less than 50 mD. The maximum pressure drop is generally controlled at 8~9 MPa for reservoirs with permeability between 50 mD and 500 mD. The maximum pressure drop can be widened to 12~15 MPa for reservoirs with permeability greater than 500 mD.

3. The Influence of Formation Pressure Maintenance Level on Oil-Water Two-Phase Seepage

Design five sets of water flooding experiments under different formation pressure conditions (5 MPa, 10 MPa, 15 MPa, 20 MPa, and 25 MPa) to obtain oil-water phase permeation curves under different pressure conditions. Using the JBN method to process the relative permeability data. The experimental results (Figures 6 and 7) show that the stress sensitivity has a great impact on the oil-water relative permeability curve. (1) As the formation pressure decreases, the irreduciblewater saturation increases. The main reason is that the core permeabilitydecreases due to stress sensitivity. And during the process of saturating oil,it is difficult for oil to drive water out of the hydrophilic rock. The resistanceof oil-water flow is increasing, which also leads to the increase ofirreducible water saturation.(2) As the formation pressure decreases, the overall permeability of the core decreases, and the relative permeability of the oil phase and the water phase decreases. The oil phase permeability decreases significantly, which leads to a decrease in producer productivity and an increase in productivity decline. (3) As the formation pressure decreases, the isotonic point decreases, and the overall oil-waterphase permeation curves shift to the left, the oil-water two-phase permeation zone narrows. It is mainly because that the stress sensitivityleads to the narrowing of the pore throats and the reduction of effectiveseepage capacity, which further reduces the oil displacement efficiency. (4) The decrease of formation pressure increases theresidual oil saturation small.

The core water drive efficiency can be expressed as [20]

$$E_r = \frac{1 - S_{wi} - S_{or}}{1 - S_{wi}}. \quad (6)$$

In the formula, E_r is the oil displacement efficiency, S_{wi} is the bound water saturation, and S_{or} is the residual oil saturation.

According to the experimental results, a mathematical model of formation pressure, bound water saturation, and remaining oil saturation is established:

$$S_{wi} = b1 \times P_i + b2, \quad (7)$$

$$S_{or} = c1 \times P_i + c2. \quad (8)$$

In the formula, $b1$, $b2$, $c1$, and $c2$ are fitting coefficients and $b1$ and $c1$ are negative.

Incorporating equations (7) and (8) into equation (6) and combined with experimental fitting data, the oil displacement efficiency equation under different formation pressures can be established.

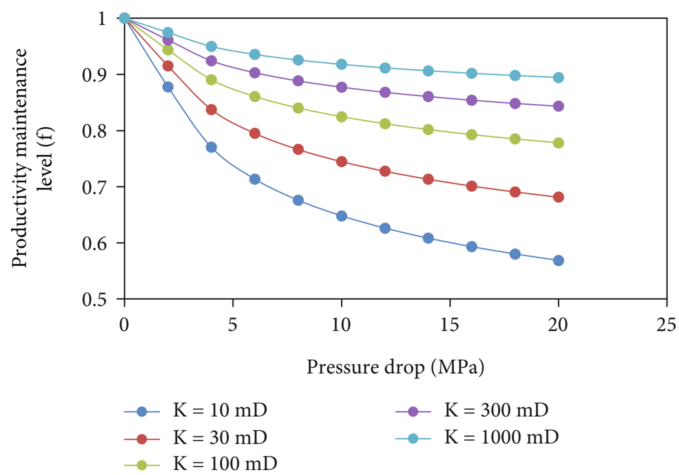

Figure 5: Effect of stress sensitivity on productivity decline (single-phase production).

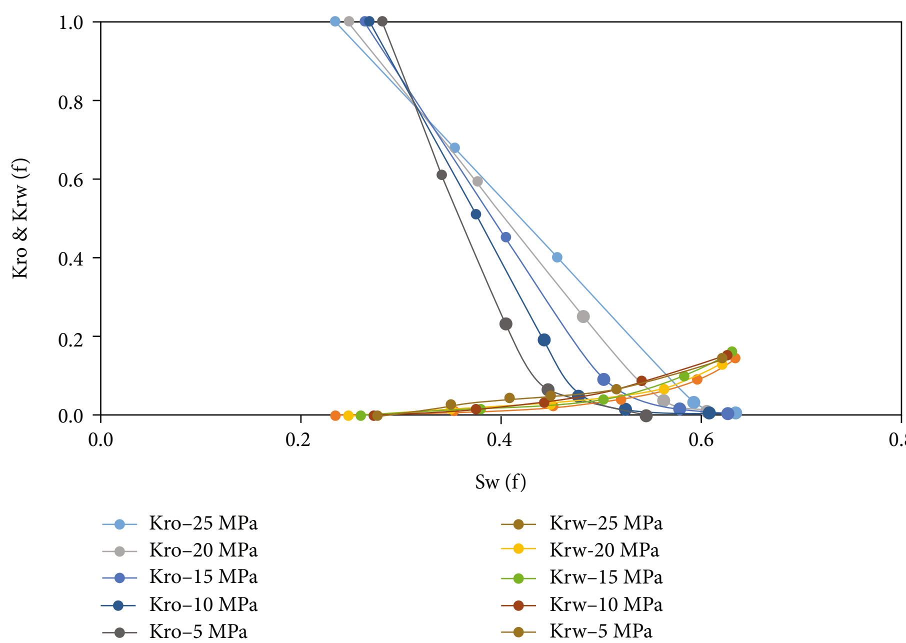

Figure 6: Oil-water phase permeation curves under different formation pressures.

$$E_r = \frac{0.0028P_i + 0.3286}{0.0023P_i + 0.7103}. \quad (9)$$

And the relationship between formation pressureand oil displacement efficiency can be drawn.The lower the formation pressure maintenance level is, the lower the oil displacement efficiency becomes (Figure 8). It is mainly caused by the formation pressure decreases. When the supporting force of the rock skeleton increases, the rock compression is serious, the pore structure is deformed, and the pore space and permeability change. Some parts of the flow channel are even closed, forming dead pores, and the oil stored in the dead pores cannot be displaced effectively.

4. Determination of Reasonable Formation Pressure Maintenance Level considering Stress Sensitivity

Based on experimental results, we interpolated the phase permeation curve in the keyword ROCKTAB and modified it corresponding to different formation pressures by setting the relevant parameters of the keyword ROCKCOMP in the oilfield simulation model, so that the influence of stress sensitivity was considered in the model.

The actual model of KLA oilfield uses the five-point method to deploy wells with a well spacing of 300 × 300 m. The simulation considers the seepage field and production

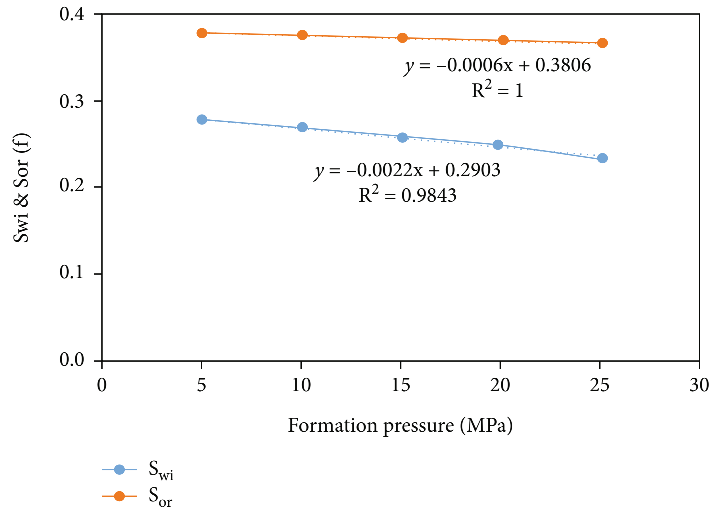

Figure 7: Relationship between S_{wi}, S_{or}, and formation pressure.

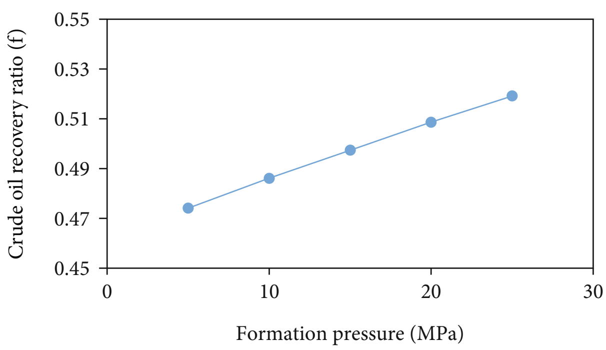

Figure 8: Influence of formation pressure on the crude oil recovery ratio.

characteristics of different development stages under stress sensitivity and clarifies the reasonable formation pressure maintenance level of reservoirs with different permeability levels (Figure 9). For reservoirs with a permeability lower than 100 mD and strong stress sensitivity, high pressure levels should be maintained. This is of great significance for protecting reservoirs near the wellbore, increasing single well production of producers and maintaining efficient and reasonable development of oilfields. For reservoirs with a permeabilityabove 300mD, under the premise that the formation pressure is higher than thesaturation pressure, the pressure can be appropriately reduced.

5. Instance Verification and Application

5.1. Instance Verification. KLA is a complex thin interbed reservoir. The existing seismic data has difficulty identifying the reservoir connectivity and the production capacity. It is necessary to test production, further access information to deepen reservoir understanding, and further identify potential reserves, productivity, and reservoir connectivity. In the marginal part of the well 2 block, the producer A24 encountered an oil layer with a thickness of 50 m and a permeability of 70 mD. A24 works well after it was put into production. The injector A23, which corresponding to A24, encountered an oil layer bottom, and the reserve scale was unclear. In the plan, A23 drains fluid at first and transfers to injection in time after A23 confirms the reserve scale. Since there is no injector in this block before, the formation pressure around A24 drops by 11 MPa, which leads to reservoir stress sensitivity, permeability reduction, and productivity decline. After the A23 transferring to injection in the later period, the productivity of A24 recovered gradually. However, the production capacity is much lower than the initial level (Figure 10). In the well 3 block with a permeability of about 300 mD, the marginal injector B14 drainages to verify the productivity at first. During the drainage, the corresponding producer B12 showed a stable initial liquid volume. After the formation pressure dropped significantly, the production capacity of B12 gradually decreased. And when the B14 transferring to injection in the later period, the production capacity of well B12 rebounded significantly. The actual production is consistent with the theoretical research results. For the wells in the areas with poor permeability, it is recommended to inject water synchronously to maintain the original formation pressure. In the areas with higher permeability, short-term formation pressure drops will not cause reservoir stress sensitivity. And if there is an evaluation requirement, the formation pressure can be appropriately reduced. After the evaluation task was completed, the injectors should recover water injection in time.

5.2. Guide the Preparation of the New Oilfield. The KLB oilfield is divided into multiple well blocks on the plane by the fault. In the ODP plan preparation process, in order to determine the reasonable water injection time of each well block, the stress-sensitive influence is characterized in the numerical model., and the physical properties of the different blocks are determined. Characteristics and natural energy conditions determine the timing of water injection

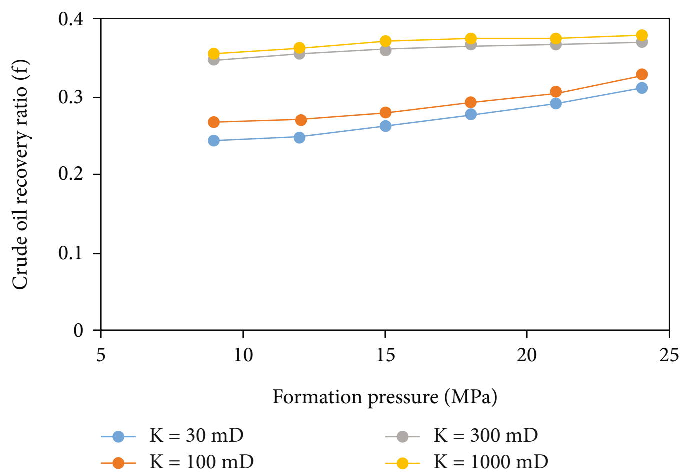

FIGURE 9: Determination of formation pressure maintenance levels of different reservoir properties.

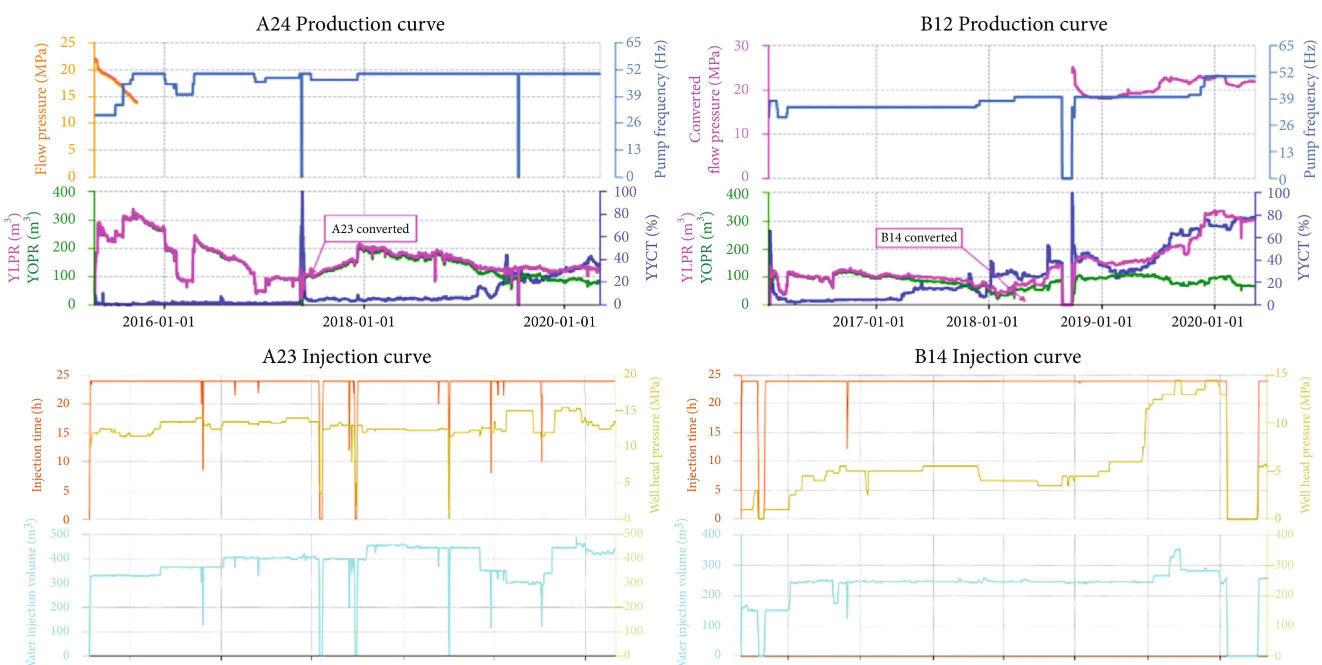

FIGURE 10: Production curve of A24, B12, A23, and B14.

TABLE 2: Comparison table of oil recovery under different pressure maintenance levels in different well areas.

Pressure maintenance levels	Well 1 area	Well 2 area	Well 3 area	Well 5 area	Well 6 area	Well 8Sa area
100%	29.8	32.6	20.8	31.8	31.2	30.0
95%	30.2	32.0	20.2	32.3	31.4	29.8
90%	29.5	30.5	19.5	31.4	30.5	29.0
85%	27.8	28.0	18.0	29.5	29.0	27.6

in each well area (Table 2). For the well 1/5/6 area with a reservoir property of 200~300 mD, considering that the ground saturation pressure difference is large and it has a certain natural energy, it is recommended to inject water after half a year after draining fluid from the injector; that is, when the formation pressure is maintained at 95%, perform water injection. For the 8Sa well area with reservoir physical properties below 100 mD, considering that the formation pressure drops, the reservoir stress will be sensitive, which will have a greater impact on productivity and seepage capacity. The program recommends that the production wells are injected immediately after commissioning to maintain the original formation pressure. For the 2/3 well area, considering that the ground saturation pressure difference is small and the natural energy is insufficient, the program recommends that the production well is put into production and injected immediately to maintain the original formation pressure. The oilfield was put into production in March 2019. After it was put into production, water injection was implemented in accordance with the recommended plan. In the two years since it was put into production, the oilfield's natural decline rate and water cut increase rate have maintained relatively good development indicators.

6. Conclusion

(1) As the formation pressure decreases, the reservoir will become stress-sensitive, resulting in a decrease in permeability and porosity. Under laboratory conditions, the formation pressure decreased by 25 MPa, the permeability of the 10 mD reservoir decreased by 46%, and the permeability of the 300 mD reservoir decreased by 17%. And the loss is irreversible. Even if the pressure returns to the original formation pressure, the permeability of the 10 mD reservoir still drops by 21%, and the permeability of the 300 mD reservoir drops by 5% which leads to a decrease in the productivity of the producers, a greater lapse rate, and a greater impact on the development effect

(2) With the decrease in formation pressure, the oil phase permeability curve is obviously concave, the point of equal permeability moves left, and the irreducible oil saturation increases. Under laboratory conditions, when the pressure decreases by 15 MPa, the irreducible oil saturation increases by 9%. And the effective seepage capacity will decrease, resulting in a decrease in oil displacement efficiency

(3) During the development of middle-deep oilfields, it is necessary to grasp a reasonable timing of water injection to ensure a higher pressure maintenance level to achieve better development results. The research results have a good guiding role in the formulation of KLB oilfield development strategies

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

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

Acknowledgments

This work is supported by "Thirteenth Five-Year Plan" National Science and Technology Major Project-Bohai Oilfield Efficient Development Demonstration Project (2016ZX05058) and CNOOC Science and Technology Project-High water cut and high recovery degree of Bohai Oilfield Key Technology Research (YXKY-2018-TJ-04).

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