Research on reasonable development strategy of offshore buried hill fractured reservoir

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Abstract. In order to improve the overall production degree of offshore buried hill fractured reservoir, expand the swept volume of water flooding, and improve the reservoir development effect, according to the actual reservoir characteristic parameters, numerical simulation software and three-dimensional physical model are used to study the reasonable pressure level, injection production mode and water flooding strategy of Oilfield A. The results show that, according to the pressure sensitivity experiment and numerical simulation analysis, the reasonable formation pressure is 70% of the original pressure for the buried hill fractured reservoir, and higher recovery can be achieved at this pressure level. By comparing different injection and production mode schemes, it is determined that under the weak injection and forcible production mode, the swept volume of reservoir water flooding is the largest, the water free recovery period of production wells is longer, and the water cut rising rate is low. The reservoir development is divided into four stages. For different stages, depressurization production, pulse water flooding, cyclic water flooding and asynchronous water flooding strategies are adopted respectively. Compared with the conventional stable water flooding strategy, the balanced development of fractures and matrix can be realized, so as to improve the full cycle development effect of the reservoir. The application of the development strategy results in this study to oilfield production practice has played an obvious role in improving the development effect of fractured reservoir, which has field practical significance and can provide reference for the development of similar fractured reservoir.

1. Introduction
Buried hill fractured reservoir is a special type of reservoir with dual medium. Compared with conventional reservoir, the pore space of this kind of reservoir changes greatly and the permeability heterogeneity is very strong. If conventional development strategy is adopted, the oilfield will face the problems of rapid water cut rise, increased production decline and short water free recovery period [1-4]. For offshore oilfields with high investment cost and short development cycle, it is difficult to bring considerable economic benefits by using conventional development methods. Therefore, it is necessary to research effective development strategies for fractured reservoirs. The existing research results are mainly about the formation mechanism and characterization of reservoir fractures [5-8], and the research objects are mainly onshore oil fields [9-12]. There are few research on the development strategy of offshore buried hill fractured reservoir [13-14]. Oilfield A is the first fractured buried hill reservoir to be developed offshore in China, and there is no mature experience for its development.
strategy. In order to ensure the oilfield to achieve good development effect in the whole development cycle, the reasonable development strategy is studied. The main research methods are numerical simulation and physical experiment. The research contents include reservoir stress sensitivity, water flooding degree, and development stage division. According to the research results, it is determined that the reasonable pressure maintaining level of Oilfield A is 70% of the original pressure, which can get higher ultimate recovery. Weak injection and forcible production mode is more suitable for Oilfield A, which can obtain higher water flooding degree. Oilfield A is more suitable to adopt reduced pressure production, pulse water flooding, and periodic water flooding and asynchronous water flooding strategy in different stages, which can get better development effect.

2. Brief introduction of Oilfield A
Oilfield A is the largest fractured buried hill reservoir in offshore China. Its lithology is gneiss and cataclastic rock. The main reservoir porosity is fracture and solution pore. Among them, structural fracture is the most developed, followed by cataclastic intergranular pore and solution pore. The porosity of the reservoir changes greatly, the permeability is very heterogeneous, and it has obvious characteristics of dual porosity medium. This study takes Oilfield A as the research object, and studies the reasonable development strategy of buried hill fractured oilfield, so as to determine the main factors to improve the development effect and enhance the oil recovery.

3. Reasonable formation pressure level

3.1. Research on reservoir pressure sensitivity
In the process of production, with the decrease of formation pressure, the pressure on the fracture system and matrix rock block system increases, which makes the fracture system and matrix system produce elastic-plastic deformation, leading to the narrowing or even closing of fracture opening. The deformation of matrix system will reduce the porosity volume, especially the throat, and greatly reduce the permeability of fracture and matrix system.

The development of fracture system in buried hill reservoir is complex. According to the statistics of logging data, the main distribution range of fracture dip angle is 50° to 75°. Therefore, fracture models with different angles are made, as shown in Figure 1. The fracture angles are 50°, 60° and 75° respectively, which are used to study the pressure sensitivity characteristics of fracture systems.

![Figure 1. Fractured core model.](image)

According to the experiment results, the pressure sensitivity curves of fracture models with different angles are drawn (Figure 2). It can be seen that the fracture models of different angles show pressure sensitivity, which indicates that maintaining reservoir pressure is very important for the development of fractured reservoirs. When the effective pressure of the model is greater than 25MPa, that is, when the pressure decreases slightly, the permeability decreases slightly, and the average permeability decrease rate is less than 20%. When the pressure decreases until the effective pressure of the model is less than 25MPa, the permeability decrease degree increases greatly, and the average permeability decrease value increases rapidly. According to the results of pressure sensitivity experiment, in order to prevent the reservoir permeability from decreasing greatly, the reservoir
pressure should be higher than 25MPa, that is, the pressure maintaining level should be higher than 67%.

![Permeability decline rate curves of fracture models with different angles.](image)

**Figure 2.** Permeability decline rate curves of fracture models with different angles.

### 3.2. Formation pressure level and recovery efficiency

In order to quantitatively study the reasonable pressure level of fractured reservoir, the pressure sensitivity experiment results are embedded into the numerical simulation software eclipse, and six comparison schemes are designed. The numerical models of different schemes are set with the same reserves, fracture reservoir ratio, initial pressure, fluid parameters and oil recovery rate, and the pressure levels are retained at 50%, 60%, 70%, 80%, 90% and 100% respectively, recovery index to determine the reasonable pressure maintenance level. The statistical results of each scheme are shown in Figure 3. When the pressure maintaining level is 70%, the cumulative oil production and recovery of the numerical model are the highest. Because the higher the pressure level is, the more sufficient the liquid supply, but the faster the water cut increase in the later stage. The lower the pressure level is, the slower the water cut increase, but it will lead to insufficient liquid supply and affect the final recovery. The results show that the reasonable formation pressure of Oilfield A is about 70% of the original pressure.

![Comparison of development indexes under different pressure levels.](image)

**Figure 3.** Comparison of development indexes under different pressure levels.

### 4. Research on injection and production mode

#### 4.1. Numerical simulation study of injection and production mode

Referring to the reservoir and fluid characteristic parameters of the actual oilfield, the geological theoretical model is established by using Petrel software [15]. According to the overall development strategy of the oilfield, combined with the fracture development law of the buried hill, and referring to the development well pattern of water flooding in the bottom horizontal wells and oil production in the top horizontal wells of the reservoir in Oilfield A, the fracture development degree is divided according to the ratio of fracture permeability and matrix permeability. The area where the ratio of fracture to matrix permeability is greater than 80 is defined as the area where fractures are developed,
and the area where the ratio of fracture to matrix permeability is less than 30 is defined as the area where fractures are not developed. According to the fracture development degree of the injection wells and production wells, four different injection and production modes are designed, namely, forcible injection and forcible production, forcible injection and weak production, weak injection and forcible production, and weak injection and weak production, as shown in Table 1.

Table 1. Design of numerical simulation schemes for injection and production mode.

| No.  | Injection and production mode               | Injection well location | Production well location |
|------|-------------------------------------------|-------------------------|-------------------------|
| Scheme 1 | Forcible injection and forcible production | Fractures are developed | Fractures are developed |
| Scheme 2 | Forcible injection and weak production     | Fractures are developed | Fractures are not developed |
| Scheme 3 | Weak injection and forcible production    | Fractures are not developed | Fractures are developed |
| Scheme 4 | Weak injection and weak production         | Fractures are not developed | Fractures are not developed |

After different schemes of water flooding, the remaining oil distributions of the numerical model are shown in Figure 4.

![Figure 4. Distribution of remaining oil in different injection and production modes.](image)

The well pattern of Scheme 1 is forcible injection and forcible production. Because of the large fracture communication between injection well and production well, it is easy to form a dominant seepage channel, which makes the production well flooded quickly, resulting in a very low degree of reserves production. The well pattern of Scheme 2 is forcible injection and weak production. Because the production wells are deployed in areas with underdeveloped fractures, the injected water is prevented from rapidly fingering along the large fractures. However, the reservoirs where the production wells are located are poor in physical properties and cannot effectively exploit the potential of the reservoir. The well pattern of Scheme 3 is weak injection and forcible production, and the permeability at the injection well is low, so the fingering is weak during the injection water displacement process, and the permeability at the production well is high, so the reservoir potential is effectively released and the injected water can be affected in a wider area, the degree of water flooding is the highest and the remaining oil is the least distributed. The well pattern of Scheme 4 is weak injection and weak production. Because the physical properties of injection well and production wells are both poor, although the injection water fingering is weak, the overall water flooding spread is not as good as that of Scheme 3.

By judging the change of oil saturation value in the numerical model grid, the number of grids to be affected by water wave is determined, and then the extent of water flooding is determined. The extent of water flooding under forcible injection and weak production mode and forcible injection and weak production mode is 13.6% and 26.2%, respectively, while the extent of water flooding under
weak injection and forcible production mode and weak injection and weak production mode is 58.5% and 53.1%, respectively. The weak injection and forcible production mode is more suitable for Oilfield A.

4.2. Research on physics experiment of injection and production mode
The core physical model has more complex permeability characteristics and is closer to the real reservoir conditions. Therefore, simultaneous injection and production mode optimization experiments can effectively verify the accuracy of the numerical simulation research results. According to the Warren-Root model, the complex fracture model is simplified to consist of a mutually perpendicular fracture system and a matrix cut by the fracture system. The physical properties and fluid parameters of the model still refer to the actual situation of Oilfield A. Considering the investment cost and time limit of the three-dimensional physical experiment, water flooding experiments were carried out on the weak injection and forcible production mode and forcible injection and forcible production mode. The relationship between recovery degree and water cut under different scenarios is calculated. As shown in Figure 5, under the forcible injection and forcible production mode, the model has a short waterless recovery period, and the water cut rises quickly after water breakthrough, and the final recovery efficiency is 17.4%. In the weak injection and forcible production mode, the model has a long waterless recovery period, and the water cut rises slowly after water breakthrough. The final recovery efficiency is 21.0%, and the development effect is better. Therefore, the results of physical experiments are consistent with the conclusions of numerical simulations.

5. Research on water flooding strategy

5.1. Division of development stages
In order to study and optimize the water flooding strategy, the basic scheme is the conventional stable water flooding development mode, that is, the injection production ratio is set at 1.0, and the constant water flooding is used for pressure maintaining production. Tracer technology is applied in Eclipse software to realize the splitting of produced fluid, so as to quantitatively characterize the oil production of fractures and matrix. Under the condition of stable water flooding, the production is finished when the water cut reaches 98%. According to the dimensionless oil production and production change trend in fractures and matrix, the whole production process is divided into four stages (As shown in Figure 6).
In the first stage (water cut <20%). This stage is the initial stage of development. The oil production rate is relatively high, but the matrix is basically not produced. The fracture oil production is absolutely dominant, and the fracture oil production decline rate is small; in the second stage (water cut between 20% to 40%), The matrix oil production began to rise gradually and reached the peak, while the fracture oil production dropped sharply, the decline rate became larger, and gradually approached the matrix oil production; in the third stage (water cut between 40% to 80%), the fractures The oil production is close to that of matrix. The rate of decline in the oil production of the fractures and the matrix slows down, and the production state is relatively stable; in the fourth stage (water cut >80%), it enters the low recovery rate stage and gradually moves towards the end of the development. The oil production of the whole reservoir is at a low level.

5.2. Unstable water flooding strategy
According to the main contradictions in the various stages of conventional stable water flooding, construct an unstable water flooding strategy for fractured reservoirs, and determine the strategies for the four stages in order of depressurization exploitation, pulse water flooding, periodic water flooding and asynchronous water flooding, thereby maintaining the formation pressure, restraining the rapid rise of water cut, and increasing the oil production of the matrix in the reservoir.

Depressurization production is applied in the first stage. At the initial stage of development, the reservoir energy is sufficient, and if the water flooding is implemented too early, it will face the risk of breakthrough in advance. Adopting the strategy of depressurization can effectively produce the original oil reserves in the matrix and fractures.

Pulse water flooding is applied in the second stage. The pulse water flooding process can be divided into two stages: pressure rise and pressure reduction: in the pressure rise stage, the oil and water in the fracture are displaced, the pressure in the fracture is higher than the inside of the matrix, and water is injected into the matrix; in the pressure reduction stage, the pressure in the fracture is lower than that of the matrix, and part of the fluid in the matrix flows into the fractures to be produced, thereby prolonging the low water cut oil recovery period.

Cyclic water flooding is applied in the third stage. The process of cyclic water flooding includes two stages: water flooding and stop flooding. In the water flooding stage, the injected water plays the role of oil displacement and pressure increase in the main fractures. In the stop flooding stage, the fluid in the secondary fractures and matrix begins to flow to the main fractures, and the liquid production of production wells decreases, but at the same time, the water cut decreases greatly, which makes the oil production increase.

Asynchronous water flooding production is applied in the fourth stage. At this time, most of the crude oil in the fracture has been produced, and the focus of development begins to shift to improving the displacement degree of oil in the matrix. The asynchronous water flooding strategy injects water into the injection wells in the process of increasing pressure, which the production wells will be shut, and the water channeling can be inhibit. In the process of depressurization, the injection wells will be
shut, the production wells will be produced, and the remaining oil in the matrix will be further utilized by using the effect of matrix expansion and capillary imbibition, so as to improve the development effect.

6. Field application practice
The above research results have been applied to the development of Eastern well block of Oilfield A. The original plan of Eastern well block is 2 injection and 5 production well pattern, and the production wells are deployed in the middle of the reservoir. Compared with the original plan, there are many new small faults in the reservoir and the understanding of reservoir structure and fault development degree is clearer. As shown in Figure 7, compared with the original scheme, the injection and production well spacing is increased, and the injection wells are deployed in the fracture undeveloped area at the low part of the structure, while the production wells are deployed in the fracture developed area at the high part of the structure, forming the mode of weak injection and forcible production.

In the initial stage of development, natural energy development is adopted. When the pressure drops to about 70% of initial pressure, water flooding development is started. The strategies of pulse water flooding, periodic water flooding and asynchronous water flooding are implemented in different stages. After the Eastern well area of the Oilfield A was put into development, the average daily oil production of a single well in the first three years increased by 96 m$^3$ compared with the original plan design, and a longer waterless recovery period was obtained. The actual cumulative oil production is predicted to increase by $20.3 \times 10^4$ m$^3$ compared with the original plan. The recovery efficiency of the Eastern well area was increased by 2.5%. It shows that the results of this study can effectively guide the development of buried hill fractured reservoirs.

7. Conclusions
Some concluding remarks of the present study are briefly explained as:

(1) According to the actual characteristic parameters of oilfield, the physical experimental study on pressure sensitivity of fractured reservoir in Oilfield A is carried out. It is found that when the pressure drops to 70% of the original pressure, the physical property of reservoir will not be damaged. Combined with numerical simulation, higher oil recovery efficiency can be achieved under the 70% of the original pressure.

(2) Combining numerical simulations and three-dimensional physical experiments to compare the effects of different injection and production modes, it is obtained that the weak injection and forcible production mode can increase the extent of injected water and effectively inhibit the phenomenon of water flooding channeling, thereby improving the water flooding effect of fractured reservoirs.

(3) Based on the permeability characteristics of fractures and matrix in fractured reservoirs, the reservoir development divided into four stages. The different stages adopt reduced pressure production, pulse water flooding, periodic water flooding and asynchronous water flooding, compared with

![Figure 7. Injection and production mode optimization of Eastern well blocks.](image)

(a) Well pattern designed
(b) Actual well pattern
conventional stable water flooding strategies. It can effectively develop fractures and matrix reserves and improve the overall development effect of fractured reservoirs.

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