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Research Article

Laboratory Investigation on Optimum Selection of a Sand Control Method for an Interbedded Sandstone and Mudstone Reservoir

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It is critical to select an optimized sand control method for an interbedded sandstone and mudstone reservoir (ISMR) due to its serious sand production hazards. However, currently, most general sand control methods cannot meet the requirements of sand control in interbedded sandstone and mudstone reservoirs (e.g., Bohai Bay oil and gas fields from China). Ensuring efficiency of sand control and increasing the oil and gas production rate in this interbedded sandstone and mudstone become more and more important. In this paper, a "multilayer rotatable sand control experimental device" for the interbedded sandstone and mudstone reservoir was developed. A series of sand control experimental studies were conducted by using the proposed device. The net-to-gross ratio (NTG) and well inclinations are two major factors considered in the experimental analysis. In addition, a sensitivity analysis regarding formation particle size distribution (PSD), clay content, and mineral compositions is performed in the experiment under a moderate sand control mode. With systematic experimental test results in this work, combined with numerous existing sand control models, a set of optimum sand control design and the associated optimization template for ISMR were developed, which have been successfully applied in Bohai Bay. Field application results show that NTG and well inclination are two critical parameters in the design of sand control in ISMR. The optimal indexes of a sand control mode are determined as NTG of 0.4 and well inclination of 45°. The introduction of these two key factors in sand control design broadens the application range of moderate sand production.

1. Introduction

In Bohai Bay, large and high-quality oil and gas fields have been developed for a long time and are maturing [1, 2]. More and more attention has been paid to the exploration and stimulation of numerous small scattered reservoirs featured with thin layers of sandstone and sand-clay interlayers [3, 4]. The thickness of this type of sandstone reservoir is generally less than 0.1 m, which makes the design of a sand control method more difficult. Currently, many representative sand control methods have been developed for sand control based on different theories [5–7], such as the Saucier method, Tiffin method [8], George method [9], and CNOOC's sand control template by Deng Jingen from China University of Petroleum in Beijing [10, 11]. The Saucier method is mainly based on the median size (d_{50}), and the Tiffin method considers the uniformity coefficient ($\mathrm{UC}(d_{40}/d_{90})$), sorting coefficient ($\mathrm{Sc}(d_{10}/d_{95})$), and fine particle content (less than 44 μm). The George method considers the uniformity coefficient (UC), the absolute range of median size (d_{50}), and the relative fluctuation range of median size (d_{50}). Deng Jingen's sand control template is determined by considering the uniformity coefficient (UC), median size (d_{50}), clay content, and montmorillonite content. These methods have been successfully applied in sand control operations. However, few of them are specifically designed for the interlayered sandstone and mudstone reservoir. It is a big challenge to increase oil and gas production rates in these reservoirs while ensuring high efficiency of sand control

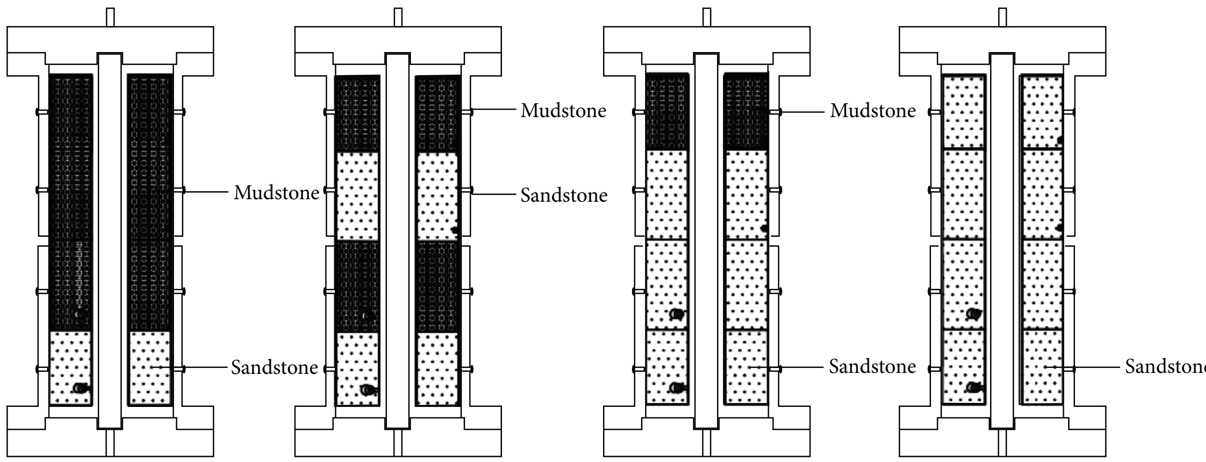


Figure 1: Schematic diagram of ISMR simulation.

[12, 13]. Major problems in the oil and gas production in the ISMR are as follows: (1) extreme heterogeneity of interlaced sandstone and mudstone makes the design of sand control more difficult and (2) the plugging mechanism of sand particles and clay minerals on the outer surface of the sand control screen is different from the plugging mechanism of sand particles and clay minerals on the blocking medium inside the sand control screen. Muddy interlayer migration occurring in oil and gas production leads to the plugging of mixed sand and mud particles, which will decrease the production rate even with a sand control operation. And there is no efficient evaluation system to predict the effects of the plugging of mixed sand-mud particles during oil and gas production.

Therefore, the aim of this paper is to develop a sand control simulation device for offshore ISMR and conduct systematic sand control experiments in multilayer reservoirs by using the proposed device. With a large number of experimental results, a set of optimum sand control design methods regarding ISMR was established, which is very helpful in enhancing the oil and gas production in ISMR.

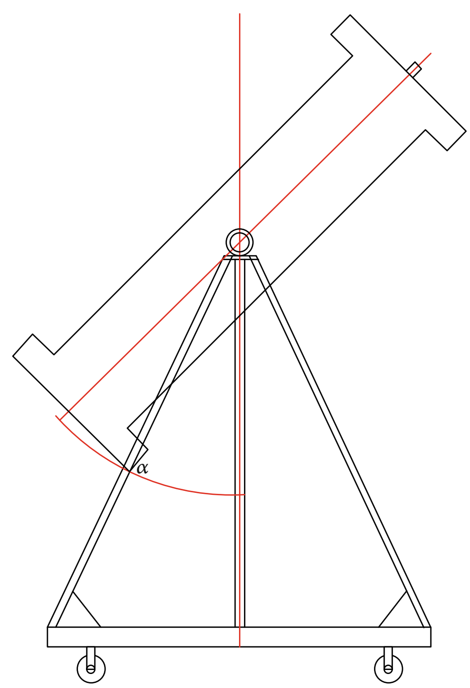


Figure 2: Schematic diagram of dynamic rotation of the wellbore.

2. Experimental Design and Evaluation System

2.1. Experimental Design Innovations. This paper built a realistic experimental device for sand control in ISMR focusing on two major factors of sand control: (1) net-to-gross ratio (NTG), which is defined as the proportion of sandstone content in the whole reservoir and reflects the distribution characteristics of interlayered sandstone and mudstone, and (2) well inclinations, which reflect the trajectories of production wells.

The reported sand control devices were mainly designed for simulating sand production in a single reservoir layer, such as a unidirectional and radial displacement device [14] and full-scale sand production device [15, 16], but few of them can consider the effects of interlayer interference or mutual channeling on the plugging of a sand control screen [14, 15]. To comprehensively consider these effects in the sand control laboratory investigation, it is necessary to stratify the multilayers of sandstone and mudstone of the ISMR and quantitatively predict the proportions of sandstone layers and mudstone layers in ISMR, as shown in Figure 1.

Most existing sand control tests are developed for vertical wells, such as a moderate sand production test [10]. Wellbore breakouts induced by arbitrary well trajectories affect fluid flow and particle plugging in sand control, but it is generally ignored in existing sand control methods. The dynamic adjustment of well inclinations in the sand control device (Figure 2) can simulate the effect of arbitrary well inclinations on wellbore breakouts and therefore fluid flow and particle plugging in sand control.

2.2. Experimental Evaluation Index. This experiment is aimed at evaluating the plugging mechanism of sand control screens resulting from clay and sand migration due to series sand production or wellbore collapse in the interlayered

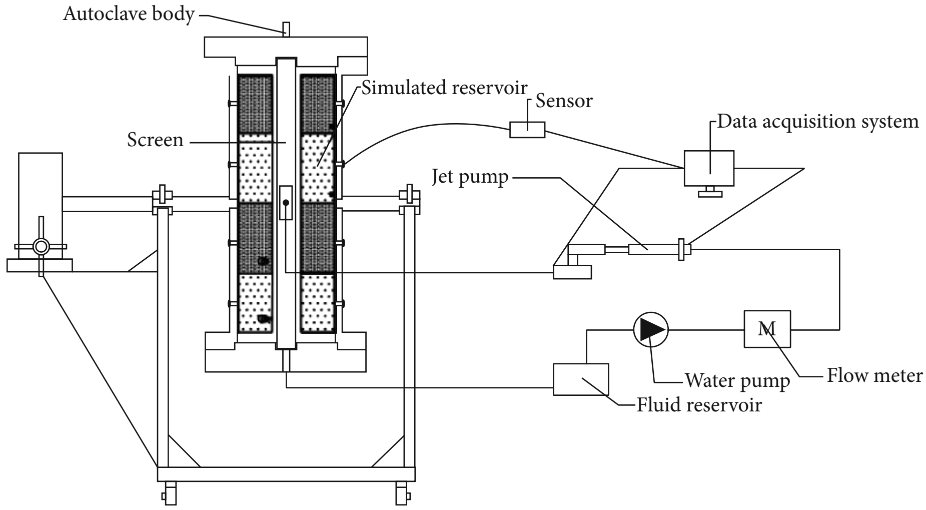
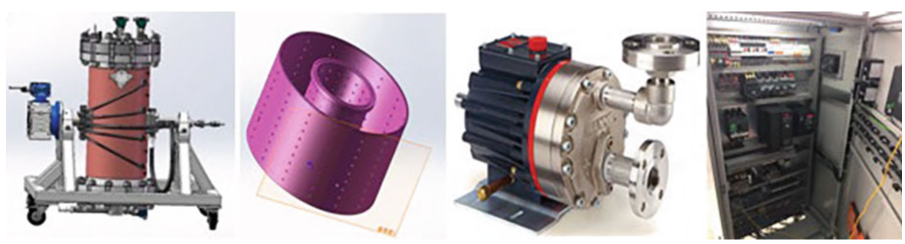


FIGURE 3: Illustration of the sand control experimental device.



Autoclave body wellbore system | Reservoir simulation sand filling system | Liquid supply circulation system | Data acquisition system

FIGURE 4: Schematic diagram of the sand control experimental device.

sandstone and mudstone reservoir. In addition, the experimental study is aimed at exploring the critical interval of increasing blockage of a sand control screen and demonstrates the scope of application of an independent sand control screen in moderate sand production. The flux capacity (i.e., the average permeability of a sand control screen, K) is used in this experiment as the evaluation index. When the sand-clay carrier fluids flow through the sand control screen or the gravel layer, the sand and clay particles carried by the fluid will gradually plug the sand control screen. As a result, the screen flow area decreases and the resistance increases, which causes a corresponding change in both pressure difference and flux rate between the inside and outside of the sand control screen. The pressure and flow rate, inside and outside the screen, are recorded in real time by the pressure sensors and flow meters. Combined with Darcy's law, the average permeability of the sand control screen can be determined as follows [17]:

$$K = \frac{q\mu}{2\pi h \Delta p} \ln \frac{D_0}{d_i}, \quad (1)$$

where K is the average permeability of the sand control screens (μm^2), q is the flux rate through the sand control screen (m^3/s), μ is the fluid viscosity (mPa·s), h is the filtration length of the sand control screen (m), Δp is the pressure difference between the inside and outside of the sand control screen (MPa), and D_0, and d_i are the outer diameter and inter diameter of the test screen, respectively (m).

3. Full-Scale Sand Control Screen Experiment

3.1. Experimental Device. The "multilayer rotatable sand control experimental device" is mainly composed of four parts: a wellbore autoclave system, a wellbore sand filling system, a reservoir oil and gas circulation system, and a data acquisition system, as shown in Figures 3 and 4. The wellbore autoclave system was designed to simulate the reservoir, wellbore annulus, and full-size sand control screen. The wellbore sand filling system simulates the realistic reservoir conditions by designing the particle size distribution, clay content and component, and net-to-gross ratio. The reservoir oil and gas circulation system includes the oil supply at an outer reservoir boundary, the radial flow of oil and gas through the reservoir, the migration of sand and clay carried by fluid through the reservoir and wellbore annulus, and the plugging of a sand control screen during the oil and gas production process. The data acquisition system uses flow and pressure sensors to collect parameters such as the flux rate through the reservoir and the sand control screen and internal and external pressures of the sand control screen and thereby calculates the average permeability of the sand control screen.

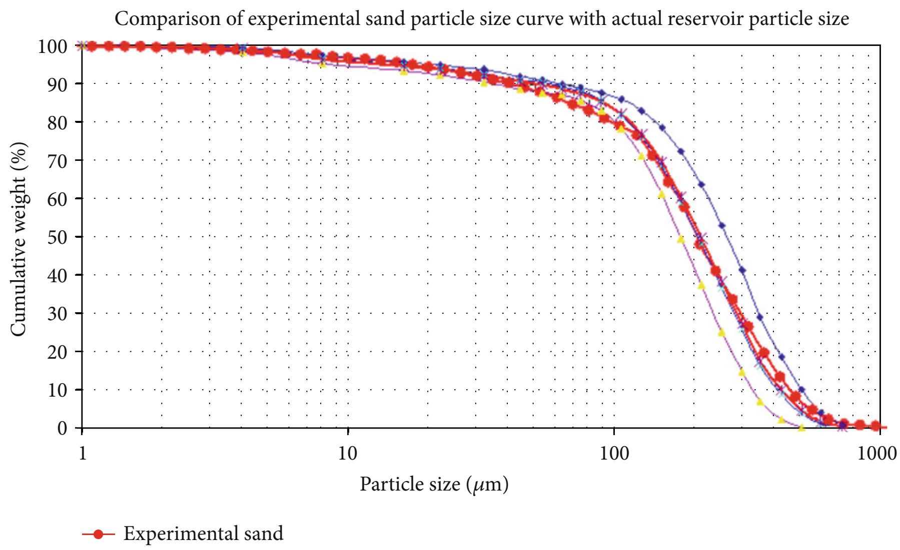


Figure 5: PSD comparison between the experimental sand and the reservoir.

Figure 6: Metal mesh premium screen.

Table 1: Two methods for determining the sand control parameter range.

d_{50} (μm)	Design objects	Design method	Sand control precision (μm)
200	Stand-alone screens (SAS)	Moderate sand control method (1.0-1.25 d_{50})	225
200	Open hole gravel pack (OHGP)	Saucier (5-6 d_{50})	16-30 mesh

3.2. Experimental Conditions

(A) Reservoir Simulation. The simulation is done as follows:

(i) The reservoir characteristics of interlayered sand and clay distribution are simulated by changing the thickness of the sand layer (i.e., net-to-gross ratio (NTG))

(ii) The realistic reservoir can be obtained by designing the required parameters of particle size distribution, such as d_{10}, d_{40}, d_{50}, d_{90}, and UC (the degree of agreement between real reservoir data and the designed data in the test is more than 90%)

(iii) The mudstone is simulated by at least setting the mineral composition according to realistic reservoir data with the accuracy being more than 90%

(iv) The test formation sand is used with the standard industry sand. The test formation layer can be prepared by adjusting the proportion of different industrial mesh-size sand, as shown in Figure 5

(B) Underground Crude Oil Simulation. Due to the difficulty in obtaining underground crude oil, industrial white oil was used to simulate the viscosity of crude oil at underground temperature.

(C) Gravel Layer Simulation. The industrial ceramsite sizes are 16-30 mesh, 20-40 mesh, and 40-60 mesh.

(D) Full-Size Sand Control Screen. The laboratory sand control screen adopts a metal mesh premium screen which meets the American API mesh standard, as shown in Figure 6.

Figure 7: Experimental flowchart.

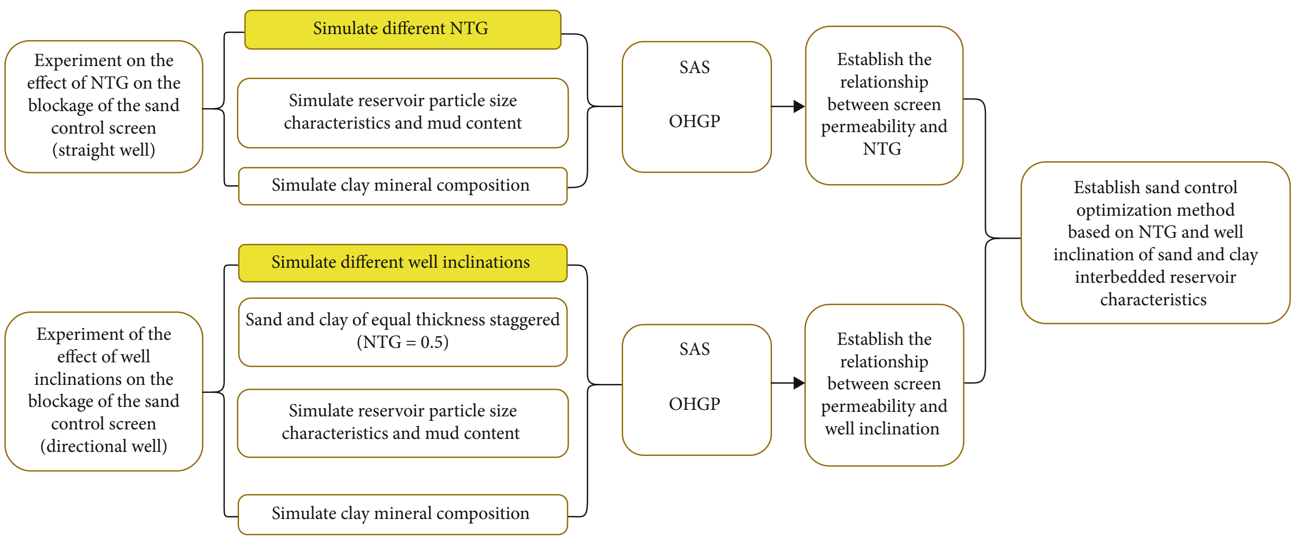


Figure 8: The experimental scheme.

According to PSD of the reservoir, the reasonable sand control precision and gravel packing size of the sand control screen are determined [10, 11, 18], as shown in Table 1.

3.3. Experimental Steps. The experimental procedure is as follows:

(1) Preparing Sand. Fill sand in four layers of a movable container (Figure 7) according to the actual formation NTG. Put them into the autoclave layer by layer.

(2) Fixing a Sensor. After sand filling, connect and seal the sensor.

(3) Base Sealing. Fix the rubber ring at the bottom of the device and apply the sand control screen to seal the bottom of the device.

(4) Top Cover. Put the top cover on top of the sand control screen (the exhaust valve is open) and apply axial pressure to seal it.

(5) Sealing. Seal the cover and install the screw buckle for sealing.

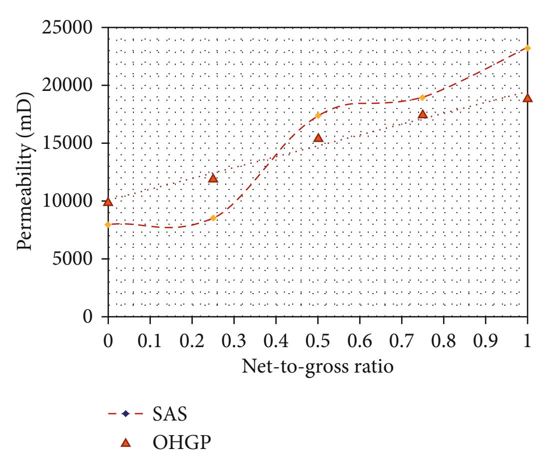


Figure 9: The effect of different NTG on the permeability of the screen.

(6) Closing the Outlet Valve and Keeping Other Valves Open. Run the pump to provide a small fluid displacement; consequently, empty the air in the kettle and then close both the pump and the exhaust port and open the outlet valve.

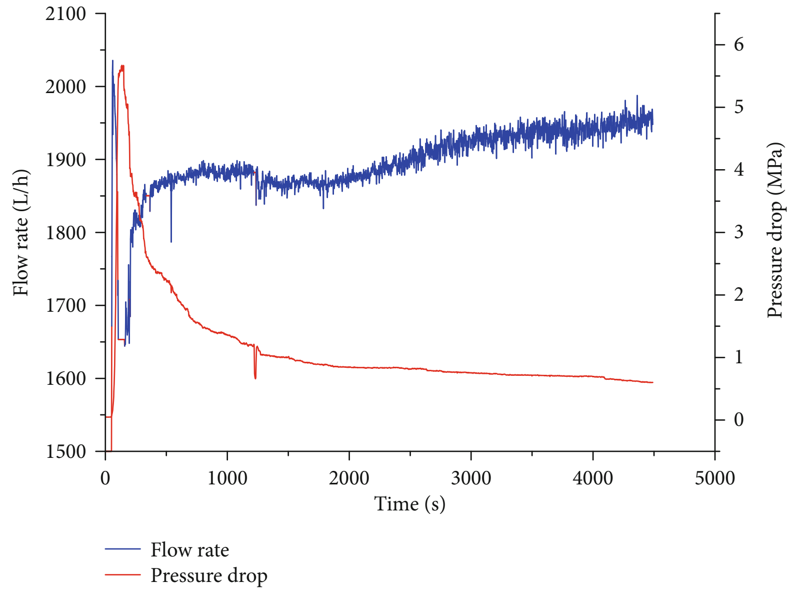


Figure 10: Experimental flow test curve (NTG = 1).

Table 2: Experiment of the effect of NTG on the sand blocking screen plugging rule under a vertical wellbore.

Sand control method	Sand control parameters	NTG	Flow rate (L/h)	Pressure drop (MPa)	Permeability (mD)
	225 μm	0	1775	1.542	8011.86
	225 μm	0.25	1810	1.480	8512.09
SAS	225 μm	0.5	1900	0.760	17400.41
	225 μm	0.75	1920	0.705	18955.34
	225 μm	1	1960	0.588	23200.54
	16-30 mesh	0	1800	1.25	10022.64
	16-30 mesh	0.25	1850	1.073	12000.28
OHGP	16-30 mesh	0.5	1870	0.84	15494.65
	16-30 mesh	0.75	1910	0.759	17515.04
	16-30 mesh	1	1930	0.709	18946.57

(7) Running the Data. Open the data acquisition software, start the pump and slowly increase the flow rate to the rated flow rate, observe and record the changes of flow rate and pressure difference in real time, stop collecting data after 1 hour of stability, and terminate the experiment.

3.4. The Experimental Scheme. The whole experiment is divided into two steps, as shown in Figure 8.

Step 1. Simulate the characteristics of the reservoir by changing the NTG content. The sand control screen plugging curve with the change of NTG in the production process of a vertical well is established. And a sensitive study regarding its various factors was performed.

Step 2. Simulate the characteristics of the reservoir by changing well inclinations for sand and clay layers with equal thickness. The plugging curve of the sand control screen with well inclination during the directional well drilling is established, and the influence of the wellbore collapse on the sand control screen is analyzed.

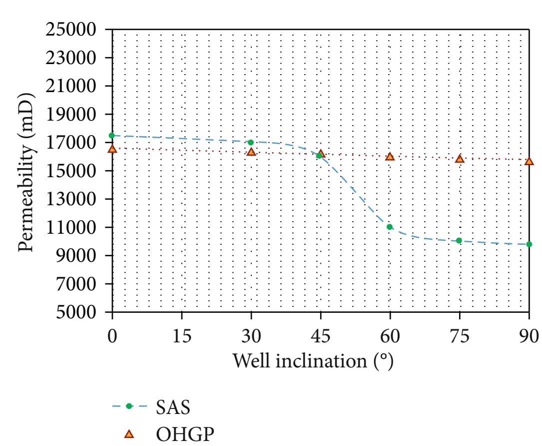


Figure 11: The effect of different well inclinations on the permeability of the screen.

Table 3: Experiments of the effect of well inclination on the blockage of a screen under directional wells.

Sand control method	Sand control parameters	Well inclination (°)	Flow rate (L/h)	Pressure drop (MPa)	Permeability (mD)
SAS	225 μm	0	1900	0.758	17446.31
	225 μm	30	1850	0.800	16095.37
	225 μm	45	1835	0.800	15964.87
	225 μm	60	1760	1.123	10908.18
	225 μm	75	1680	1.160	10080.23
	225 μm	90	1640	1.17	9756.126
OHGP	16-30 mesh	0	1870	0.79	16475.32
	16-30 mesh	30	1860	0.789	16407.98
	16-30 mesh	45	1845	0.79	16255.06
	16-30 mesh	60	1820	0.792	15994.31
	16-30 mesh	75	1812	0.796	15843.98
	16-30 mesh	90	1810	0.81	15552.95

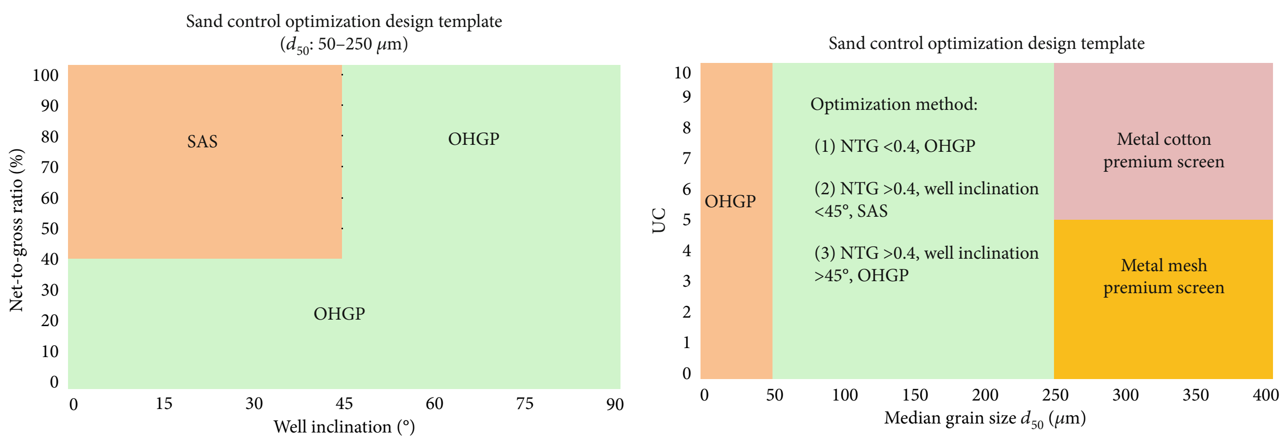


Figure 12: Sand control method for ISMR.

4. Results and Discussion

4.1. Effects of NTG on Sand Control Screen Plugging of Vertical Wells. Due to the existence of the annulus for stand-alone screens (SAS) for sand control, the mudstone layer flows to the outer surface of the entire sand control screen under the fluid, causing the overall blockage of the SAS; the gravel layer of open hole gravel pack (OHGP) limits the longitudinal flow of the mud, which will reduce the influence of this factor. In order to quantitatively analyze the effect of NTG on the choice of sand control methods, taking the reservoirs in Minghuazhen in Bohai Bay as a reference, parameters such as PSD and clay content and component are simulated. Considering the characteristics, the sand production simulation experiment under different NTG (0/0.25/0.50/0.75/1) was carried out. The simulation effect of NTG is shown in Figure 1. The initial flux rate of the experiment is calculated as 2000 L/h according to the output of a single well in the oilfield, the circulating medium uses industrial white oil with a viscosity of 80 mPa·s to simulate underground crude oil, and 10 groups of simulation experiments with different NTG are carried out (as shown in Figure 9). Figure 10 shows the variation of pressure and flux rate with time when the NTG is equal to 1 for SAS, and the entire experimental test data is shown in Table 2.

Table 4: Reservoir characteristic statistics of the Minghuazhen Formation in the PL oilfield.

Reservoir characteristics	Range of reservoir characteristics
Median grain size (d_{50})	150-250 μm, average 200 μm
Sand uniformity coefficient (UC)	5~10
Fine particles smaller than 44 microns	10~20%, average 15%
NTG	0.4~0.6, average 0.485
Production well type	Directional well Well inclination 30°~45°
Clay content	20%
Montmorillonite content	<5%

The experimental results show that the NTG of 0.4 is the intersection point of SAS and OHGP. When the NTG is above 0.4, the screen plugging caused by the interchanneling of SCIR for SAS is lower than the plugging of OHGP under the same conditions. So in the optimization of field sand

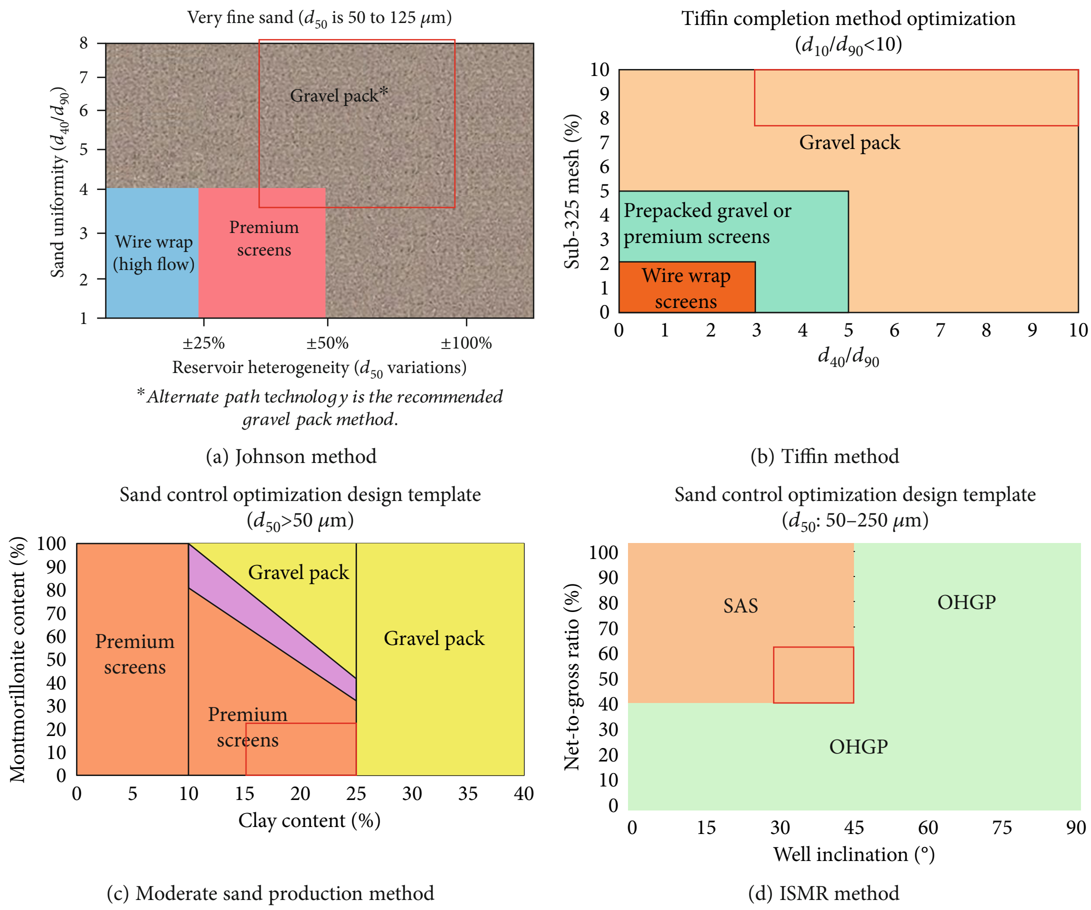


Figure 13: (a) Johnson method, (b) Tiffin method, (c) moderate sand production method, (d) ISMR method.

control methods, when NTG is higher than 0.4, SAS can be preferred.

4.2. Effects of Well Inclinations on Plugging of the Sand Control Screen for Deviated Wells. As the well inclination increases, the risk of wellbore collapse increases during oil and gas production. To study the plugging mechanism of the sand control screen due to microparticle migration resulting from wellbore collapse in deviated wells, contrast experiments are carried out under various well inclinations. The primary experimental conditions of the control are NTG = 0.5, and the reservoir ratio is 1 : 1 sand-mud mixture (the reservoir consists of 4 layers (mud-sand-mud-sand, from top to bottom)); the viscosity of the circulating medium is 80 mPa·s. Industrial white oil is used to simulate underground crude oil. 12 groups of simulation experiments with different well inclinations are carried out (as shown in Figure 11). The experimental test data is listed in Table 3.

The experimental results show that the annulus is filled with a gravel layer for OHGP; there is no risk of borehole collapse during drilling. When NTG is constant, the change in well inclinations has little effect on the blockage of OHGP. For SAS, the wellbore collapse intensifies at the inclinations between 30° and 60°. The blockage degree of SAS is higher than that of OHGP when the well inclination exceeds 45°. Therefore, the well inclination must be considered in designing an optimized sand control mode in fields.

5. Sand Control Design and Template for ISMR

On the basis of numerous existing sand control methods and a series of tests results in this paper, a set of optimum sand control design and the associated optimization template for ISMR were developed, as shown in Figure 12.

(1) $d_{50} < 50\ \mu$m (OHGP)

(2) $50\ \mu\text{m} < d_{50} < 250\ \mu$m:

(i) NTG < 0.4 (OHGP)

(ii) NTG > 0.4 and well inclination < 45° (SAS)

(iii) NTG > 0.4 and well inclination > 45° (OHGP)

(3) $d_{50} > 250\ \mu$m (SAS):

(i) UC > 5 (metal cotton premium screen)

(ii) UC < 5 (metal mesh premium screen)

6. Field Application of the Sand Control Design for ISMR

The Minghuazhen Formation reservoir in the PL block of Bohai Bay is the case study considered in this paper. Table 4 lists the reservoir characteristics. The sand control design for the PL block is studied by applying the foreign Johnson method, Tiffin method, moderate sand production method, and sand control design for ISMR established in this paper, separately. The Johnson and Tiffin methods both recommend the use of OHGP in this field by considering extremely heterogeneous reservoirs with high content of fines and silts (as shown in Figures 13(a) and 13(b)). This design is relatively conservative; thus, it is not quite suitable for high productivity. However, the design method established in this paper takes into further consideration factors such as well inclination and NTG. A good quality of SAS can be used for sand control to prevent serious plugging of the sand control screen (as shown in Figures 13(c) and 13(d)), which can greatly increase the production capacity. The sand control method is consistent with the moderate sand control method and has been verified by on-site productivity statistics.

7. Conclusion

(i) The sand control design for an unconsolidated sandstone reservoir needs to take into consideration the d_{50}, UC, and clay constituents. According to the design characteristics of ISMR, NTG and the angle of well inclination were added based on previous studies. This design broadens the application scope of moderate sand mining and fills domestic research gaps in this field

(ii) Through a large number of in-house sand production simulation experiments, the blocking mechanism of the sand control screen caused by mudstone channeling and wellbore collapse in ISMR is revealed. The optimal indexes of the sand control mode are determined as NTG of 0.4 and well inclination of 45°, and thus, we establish a new sand control design method

(iii) This sand control design method has been applied in potential tapping, production, and sand control mechanism for many old oilfields in Bohai Bay, and it has shown encouraging field results. However, this design method still lacks proper theoretical background further, and extensive research work is required to further improve it

Nomenclature

ISMR:	Interbedded sandstone and mudstone reservoir
NTG:	Net-to-gross ratio
SAS:	Stand-alone screens
OHGP:	Open hole gravel pack
PSD:	Particle size distribution
d_{50}:	Median grain size
UC(d_{40}/d_{90}):	Sand uniformity coefficient

Data Availability

All data generated or analyzed during this study are included in this published article.

Conflicts of Interest

None of the authors have any conflicts of interest.

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References

[1] X. L. Zeng, F. J. Sun, and X. Wang, “Simulation experimental study on sand production law of Bohai heavy oil reservoir under simple sand control condition,” *China Offshore Oil and Gas*, vol. 6, pp. 36–41, 2004.

[2] B. Wang, L. L. Xu, M. Wen, and Z. L. Fan, “Practical analysis of sand control in multi-layer thin interbedded heavy oil reservoir in Bohai Bay,” *Oil Drilling & Production Technology*, vol. 40, no. 6, pp. 818–822, 2018.

[3] X. C. Jin, Q. L. Zhang, and S. C. Gao, “Sand production mechanism, influencing factors and sand control technical countermeasures of heavy oil reservoir- based on sand control practice of heavy oil reservoir in Liaohe oilfield,” *China Offshore Oil and Gas*, vol. 329, no. 5, pp. 320–324, 2006.

[4] Y. Liu, Y. L. Yang, and J. L. Dong, “Sand control technology improvement of thin layer unconsolidated sandstone reservoir,” *Special Oil and Gas Reservoir*, vol. 5, pp. 85-86, 2017.

[5] W. Q. Huang, “Application of high pressure gravel filling sand control technology in Shu three area,” *Special Oil and Gas Reservoir*, vol. 17, no. 4, pp. 111–113, 2017.

[6] D. H. Schwartz, “Successful sand control design for high rate oil and water wells,” in *Society of Petroleum Engineers*, 2013.

[7] L. H. Wang, Y. S. Lou, and J. G. Deng, “Optimization of sand control methods and parameters in deep shallow gas fields,” *Petroleum drilling technology*, vol. 41, no. 1, pp. 98–102, 2013.

[8] D. L. Tiffin, G. E. King, R. E. Larese, and L. K. Britt, “New criteria for gravel and screen selection for sand control,” in *Society of Petroleum Engineers*, 1998.

[9] G. Gillespie, C. K. Deem, and C. Malbrel, “Screen selection for sand control based on laboratory tests,” in *Society of Petroleum Engineers*, 2000.

[10] J. G. Deng, P. Li, and L. H. Wang, “Optimum sand control methods of appropriate sand control technology in Bohai Bay area,” *Oil Drilling & Production Technology*, vol. 33, no. 1, pp. 98–101, 2011.

[11] J. G. Deng, P. Li, and J. L. Zhou, “Optimization of sand control methods in China's offshore loose sandstone production wells,” *Acta Petrolei Sinica*, vol. 33, no. 4, pp. 676–680, 2012.

[12] Y. Chuanliang, R. Xu, Y. Cheng, S. Benjian, L. Yang, and T. Wanqing, "Geomechanical issues in the exploitation of natural gas hydrate," *Gondwana Research*, vol. 81, pp. 403–422, 2020.

[13] Y. Chuanliang, L. Yang, Y. Cheng et al., "Sand production evaluation during gas production from natural gas hydrates," *Journal of Natural Gas Science and Engineering*, vol. 57, pp. 77–88, 2018.

[14] C. Y. Dong, K. G. Gao, and C. Zhou, "Plugging law experiment of sand control well and quantitative prediction model of plugging degree," *Journal of Experimental Mechanics*, vol. 32, no. 3, pp. 351–360, 2017.

[15] L. H. Wang, J. G. Deng, and J. L. Zhou, "Experimental study on sand control parameters design of standard metal mesh high quality screen for moderate sand production," *China Offshore Oil and Gas*, vol. 23, no. 2, pp. 107–110, 2011.

[16] L. H. Wang, C. Y. Dong, and Y. D. Peng, "Performance evaluation and optimization experiment of mechanical sand control screen pipe for Cretaceous reservoir in Chunguang oilfield," *Science Technology and Engineering*, vol. 15, no. 25, pp. 120–124, 2012.

[17] C. Y. Dong, B. X. Jia, and C. M. Liu, "Experiment on plugging mechanism and regularity of sand-retaining media in mechanical sand-control screen pipe," *Journal of China University of Petroleum(Edition of Natural Science)*, vol. 35, no. 5, pp. 82–88, 2011.

[18] R. J. Saucier, "Considerations in gravel pack design," in *Society of Petroleum Engineers*, 2013.