Study on the Water Blocking Capacity and Influencing Factors of Hydrophobic Gravel Beds

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1. INTRODUCTION

Although many consolidated reservoirs host oil and gas resources around the world, an increasing number of unconsolidated sandstone formations have been targeted for their significant amount of hydrocarbons, such as the Gulf of Mexico,1−12 Athabasca (Canada),13−14 Orinoco (Venezuela),15,16 and Bohai Bay Basin of China.17 Nearly two-thirds of the world’s oil resources are found in unconsolidated sandstone, which has the characteristics of shallow depth, low strength, and easy sanding.5,6,8−11 One of the most serious problems in the production of oil and gas wells is the large amount of water produced during production. High water production may cause a series of problems in oil and gas wells, such as a sharp decline in oil and gas production, and corrosion and abrasion of metal equipment.12−16 Especially for unconsolidated sandstone reservoirs, sand production phenomena are common in the development process due to their loose cementation and low strength. Once water intrusion occurs in the reservoir, it can cause some fatal hazards to the production of oil and gas wells.17−19 First, the cementing strength of rocks weakens, especially when rocks contain many water-sensitive clay minerals, such as montmorillonite.20−23 These water-sensitive clay minerals react with the reservoir water from the far end of the well and swell to weaken the bond between particles in the rock, making it easier for particles to peel off. However, severe sand production can lead to a series of problems, such as tubing pump stuck, wellbore burial, and even the stopping of the production of oil and gas wells.24−27 Second, water intrusion increases the number of particles transported to the wellbore. When the flow path changes from unidirectional flow to multiphase flow, its sand-carrying capacity increases, resulting in more solid particles being carried into the wellbore. Third, this change may cause reservoir damage through a reaction between water-sensitive minerals, formation water, and fine particle migration that may reduce the flow area of the channel, resulting in a decrease in permeability.28,29 Therefore, it is imperative to reduce the production of formation water to prolong the service life of the well.

At present, the water control measures used in unconsolidated sandstone reservoirs are mainly divided into two
types of methods: mechanical and chemical. Mechanical methods use packers in the wellbore to seal the excess water zone. Chemical methods can be achieved by using chemical plugging agents to block the rock matrix and some small fissures. Common water plugging agents are in situ gels, polymers, water swelling polymers, and micro matrix cement. However, a common drawback of both methods is that they block the flow of oil as well as water simultaneously, which will reduce oil production. This result is not usually desired by field engineers. The application of hydrophobic proppants in the petroleum industry has made it possible to solve this problem. So far, hydrophobic proppants were primarily used in near-water formation hydraulic fracturing, which can improve oil phase permeability in oil—water two-phase flow to a certain extent. For example, Tabatabaei et al. prepared hydrophobic proppants based on the inherent hydrophobicity on the surface of graphite nanoplatelets and tested the conductivity of the proppants. The experimental results showed that the effective and relative permeability of the oil phase could be improved. Similarly, novel surface-modified quartz sand proppants with double hydrophobic layers were prepared by Fu et al.; the water contact angle was 151°, and the fracture conductivity test results were the same as those of Tabatabaei et al. Through oil field tests, Jin et al. concluded that hydrophobic proppants could reduce the water production rate from 88.3% to less than 20%. Considering the water control effect of hydrophobic proppants in near-water formation hydraulic fracturing, some scholars have proposed using hydrophobic gravel in gravel packing technology and using the capillary resistance (CR) of the water phase generated by the gravel layer to delay formation water flow into the wellbore. Liu et al. conducted laboratory experiments to study the variation in the WBC of hydrophobic gravel beds with different permeabilities along with displacement pressure differences. Liu et al. studied the capillary bundle model of curved flow channels in porous media with spherical particles. In general, there are few studies on hydrophobic gravel packing technology and its WBC.

So far, the reagents used in the hydrophobic modification of quartz sand are mainly organosilane, cationic surfactant, and fluorosurfactant. For example, Wei et al. and Hou et al. prepared hydrophobic quartz sand by a surface modification method with KH550 (3-aminopropyltriethoxysilane coupling agent) as the silicon source. Men et al. reported that superhydrophobic quartz sand prepared by octadecyltrichlorosilane has great application prospects in oil—water separation. Liu et al. obtained superhydrophobic quartz sand through HMDS surface-modified nanosilica particles. Yang and Yang prepared hydrophobic-lipophilic silicas by means of polymer film self-assembly technology. In general, the preparation technologies of hydrophobic gravels in the laboratory have been relatively mature. Nevertheless, these preparation methods are complex, time-consuming, and lack some field tests. Therefore, the modification conditions of hydrophobic gravels and construction parameters on the CR and WBC should be further studied to lay a foundation for field applications.

In this paper, to study the influence of grave surface wettability and construction parameters on the WBC, hydrophobic quartz sands were prepared with the silane coupling agent 1,1,3,3,3-hexamethyldisilazane (HMDS), and the hydrophobic properties of quartz sands were characterized by the activation index and water contact angle. A theoretical capillary bundle resistance model of a quartz sand bed was also established to study the effects of gravel particle size, surface wettability, porosity, and displacement pressure difference on the CR and WBC of the quartz sand bed. The research results of this paper can provide new ideas for the water control development of high water cut oil and gas fields and provide corresponding theoretical construction parameters for on-site construction projects.

2. EXPERIMENTAL METHODOLOGY

2.1. Materials. The materials used in the experiment are shown in Table 1. The silane coupling agent HMDS, methylene blue, and ethyl alcohol were supplied by Shanghai Macklin Biochemical Co., Ltd. Quartz sand with a diameter of 180–250 μm was purchased from Lingshou Mineral Co., Ltd. (Hebei, China). The distilled water used in this study was prepared in our laboratory.

2.2. Preparation of Hydrophobic Gravel. First, 250 g of quartz sand was stirred and cleaned three times with 500 mL of distilled water and then cleaned with anhydrous ethanol three times to remove impurities on its surface. After cleaning, the quartz sand was filtered out and dried at 60 °C to avoid damaging the hydroxyl group on its surface. Distilled water was mixed with ethanol at a ratio of 1:9 to form a solvent, and then 100 mL of HMDS solution with mass fractions of 0.2, 0.4, 0.6, 0.8, and 1% was prepared with the solvent. HMDS was hydrolyzed by stirring for 10 min at 60 °C, and then 50 g of quartz sand cleaned in the previous step was added to the solution and the reaction was continuously stirred for 2 h. The quartz sand was filtered and dried at 80 °C for 4 h to obtain the modified quartz sand.

2.3. Wettability Characterization. The wettability of quartz sands includes the measurement of activation index and the water contact angle.

2.3.1. Activation Index. Owing to its higher density and hydrophilic surface, quartz sands will easily be wetted when immersed in water. However, the quartz sand surface modified by HMDS changes from hydrophilic to hydrophobic. At this point, due to the effect of surface tension, the modified quartz sands will not be wetted and will float on the water surface, as shown in Figure 1. According to this phenomenon, the effect of quartz sands can be judged. The “activation index” is defined as the ratio of the weight of the floating quartz sands to the total weight of quartz sands. To obtain the value of the activation index, an experimental device was established, as shown in Figure 2. First, m1 (g) of quartz sand was weighed and placed into the pear-shaped funnel filled with distilled water, stirred for a while, and allowed to sediment for 10 min. After the quartz sand particles in the pear-shaped funnel were stabilized, the valve of the pear-shaped funnel was opened to separate and filter the quartz sand deposited at the bottom of the vessel, and the quartz sand was dried to test the weight.
recorded as $m_2$. Then, the active index $H$ was calculated by eq 1.

$$H = \frac{m_1 - m_2}{m_1}$$

2.3.2. Water Contact Angle. First, the quartz sand samples before and after modification were spread on glass slides and pressed into compact layers with the glass slides. Then, the water contact on the quartz sand surface was measured by a JC2000 contact angle meter (Shanghai Zhongchen Digital Technology Equipment Co., Ltd.). Each quartz sand sample was measured three times and averaged.

3. ANALYTICAL MODEL

3.1. Capillary Bundle Model. A capillary bundle model is developed herein to analyze the influence of external conditions on the water resistance of gravel beds. The assumptions adopted to formulate the problem are as follows: (1) The gravel bed is homogenous and isotropic, and the cylindrical gravel bed with diameter $D$ and length $L$ is simplified into $n$ capillary sets with diameter $d$ and length $l$, as shown in Figure 3. The average effective diameter of packed gravel particles is $d_e$ and the porosity of the gravel bed is $\phi$. (2) The pore volume of the entire gravel bed is equal to the sum of the volume of $n$ capillaries. (3) The surface area of the gravel bed is equal to the sum of the surface areas of $n$ capillaries.

According to assumption (2) and assumption (3), eqs 2 and 3 can be obtained as follows:

$$\frac{\pi D^2 L \phi}{4} = n \pi \frac{d_e^2 l}{4}$$

$$\frac{\pi D^2 L (1 - \phi)}{4} \frac{6}{d_g} + \pi D L n = \pi d l$$

where $D$ is the diameter of the cylindrical gravel bed, $L$ is the length of the cylindrical gravel bed, $\phi$ is the porosity of the gravel bed, $d_c$ is the capillary diameter, $l$ is the capillary length, and $d_g$ is the gravel particle size.

The relationship between gravel particle size $d_g$ and capillary diameter $d_c$ can be obtained by dividing eq 2 by eq 3, as shown in eq 4.

$$d_c = \frac{2 \phi d_g}{3 (1 - \phi) + \frac{2d}{D}}$$

The capillary force formula of the spherical curved liquid surface in the equal-diameter cylindrical capillary channel can be expressed as eq 5:

$$p_c = \frac{2 \sigma \cos \theta}{r_c}$$

where $p_c$ is the capillary force, $\sigma$ is the interfacial tension between the gas and liquid phases, $\theta$ is the liquid contact angle, and $r_c$ is the capillary radius.

The capillary force generated by the capillary bundle on the liquid phase can be obtained by combining eqs 4 and 5, which can be expressed as:

![Figure 1. State of sand particles with different wettabilities when immersed in water: (a) hydrophilic and (b) hydrophobic.](image)

![Figure 2. Device for measuring activation index.](image)

![Figure 3. Schematic diagram of the capillary tube bundle model.](image)
Equation 6 shows that the $p_c$ generated by the gravel bed in the liquid phase is mainly determined by the $d_g$, porosity of the gravel bed, wetting degree of the gravel bed, and boundary shape of the selected model. To compare with the experimental results, the size of the model taken in this paper is the same as in the study of Liu et al.\textsuperscript{42}

The relationship between the permeability and porosity of a gravel bed is given by the Kozeny–Carman equation:\textsuperscript{49–51}

$$K = \frac{\phi^3}{CS_p^2}$$

(7)

where $K$ is the permeability of gravel beds, $S_p$ is the specific surface area of the gravel bed as a base for pore volume, $S_p = 2/r_s$ and $C$ is the Kozeny constant.

Assuming that the flow in the gravel bed is Darcy flow, the flow rate can be expressed as eq 8:

$$Q = f(\phi, \theta, d_g, \Delta p) = \frac{K(\phi, d_g)A(\Delta p + p_c(\phi, d_g, \theta))}{\mu L}$$

(8)

where $\mu$ is the viscosity of the fluid, $A$ is the flow area through porous media, and $\Delta p$ is the displacement pressure difference.

### 3.2. Characterization of the Water Resistance

The water resistance of the hydrophobic gravel bed mainly comes from the $p_c$ produced by the gravel deposit. Referring to the research of Liu et al.,\textsuperscript{41} $\delta$ is introduced to characterize the water-blocking capacity of gravel beds, and the specific expression of $\delta$ is shown in eq 9:

$$\delta = \frac{Q_{w,i} - Q_{w,fin}}{Q_{w,i}}$$

(9)

where $\delta$ is the water blocking capacity (WBC) of the gravel bed, $Q_{w,i}$ is the water production rate of conventional gravel filling ($\theta = 0^\circ$), mL·min$^{-1}$; and $Q_{w,fin}$ is the water production rate after changing the external conditions.
4. RESULTS AND DISCUSSION

4.1. Experimental Results and Discussion. 4.1.1. Reaction Mechanism of Quartz Sand with HMDS. Figure 4 schematically shows the reaction mechanism between quartz sand and HMDS, which includes two steps of chemical reactions.46 First, the silane coupling agent HMDS is hydrolyzed and its SiC\textsubscript{3}H\textsubscript{8} group is transformed into C\textsubscript{3}H\textsubscript{9}Si−OH (as shown in Figure 4a). Then, C\textsubscript{3}H\textsubscript{9}Si−OH that originated from the hydrolysis of HMDS reacts with the hydroxyl group on the surface of quartz sand, yielding a modifying layer on the surface of quartz sand (as show in Figure 4b). A mass of hydroxyl groups on the surface of quartz sand are replaced by SiC\textsubscript{3}H\textsubscript{9} groups, which causes a steric hindrance.47 Finally, hydrophobic quartz sands were prepared.

4.1.2. Wettability of Quartz Sand. Figure 5 shows the state of water droplets (dyed with methylene blue) on the surface of sand particle beds treated with different concentrations of HMDS. It can be clearly seen from Figure 5 that the states of water droplets on sand particle beds are significantly different before and after modification. On the surface of the untreated particle bed, water droplets penetrate into it rapidly because the sand particles are hydrophilic, and the capillary force exerted by the sand particle bed on the water droplets is downward. However, the water droplets all stay on the surface of the particle bed treated with 0.2, 0.4, and 0.6% HMDS, showing obvious hydrophobicity. This can be explained by the effect of the hydrophobicity of the treated sand, and the capillary force exerted by the sand particle bed on the water droplets is upward. In addition, the hydrophobicity of the particle bed treated with 0.6% HMDS is stronger than that treated with 0.4 and 0.2% HMDS. Therefore, hydrophobic sand particles can be successfully prepared by using a certain concentration of HMDS at 80 °C and reacting for 4 h. Consequently, the effects of the HMDS concentration on the activation index and water contact angle of the modified sand can be discussed.

The effects of different concentrations of HMDS on the surface wettability of sand particles were investigated. The activation index of quartz sand after treatment with different concentrations of HMDS is shown in Figure 6. Figure 6 shows that the initial wettability of quartz sands is water wetting because the water contact angle on the surface of the untreated sand particle bed is nearly 0°. The water droplets penetrate into the sand particle bed because the sand particles are hydrophilic. A significant increase in the water contact angles can be observed as the mass concentration of HMDS continues to increase: the water contact angle on the surface of the sand particle bed reaches 105, 125, 146, 150, and 148°, after being treated with 0.2, 0.4, 0.6, 0.8, and 1% HMDS, respectively. Compared with the activation index, the water contact angle fluctuated slightly when the HMDS concentration exceeded 0.6%. However, this fluctuation is within the allowable error range, because the water contact angle measurements differ within 4°. Because the water contact angle on the sand particle bed has a small fluctuation after the concentrations of HMDS were greater than 0.6%, the optimal concentration of HMDS can be considered to be 0.6% from the perspective of economy.

4.2. Calculation Results and Discussion. 4.2.1. Model Validation. To validate the effectiveness of this capillary bundle model, the WBC values of capillary bundles with different permeabilities were computed and compared with the experimental results of Liu et al.41 Liu et al. conducted a sand-filling pipe experiment in the laboratory to study the variation in the water-blocking capacity of hydrophobic gravel with different permeabilities along with displacement pressure differences. The gravel used in the experiment was a coated gravel with a diameter of 450 μm (40 mesh) and a water contact angle of 163°. The porosity value corresponding to each permeability is calculated by eq 7 and substituted into eqs 8 and 9 to calculate the WBC of hydrophobic gravel beds under different permeabilities. A Comparison between the
experimental results and numerical calculation results is shown in Figure 8.

Figure 8. Comparison of experimental and numerical results.

In the experiment, gravel beds with different permeabilities represent gravel beds with different compaction degrees. The smaller the permeability is, the tighter the compaction is and the smaller the porosity is. The greater the permeability is, the looser the compaction and the greater the porosity. As shown in Figure 8, when the displacement pressure difference is less than 2 MPa, the calculated values and experimental values are in good agreement.

In general, when the displacement pressure difference is less than 2 MPa, this capillary bundle model can accurately predict the WBC of hydrophobic gravel beds. It can provide theoretical construction parameters for field construction, such as gravel particle size, wettability, and displacement pressure difference.

Because the WBC of the hydrophobic gravel bed mainly comes from the capillary force generated by the gravel bed, the effects of gravel particle size, porosity, and particle surface wettability on the CR and WBC generated by the gravel bed are mainly calculated and analyzed in the following section. Finally, a field case of hydrophobic quartz sands controlling the production of formation water is discussed.

4.2.2. Effect of Gravel Particle Size. The effect of gravel particle size \( d_g \) on the capillary force is mainly reflected in the capillary radius, and the capillary radius directly determines the value of capillary force. Figure 9 illustrates the calculation results of CR under different average effective particle sizes of the gravel bed. Figure 9 shows that with increasing the average effective particle size, the CR decreases rapidly and changes with the porosity and water contact angle. This can be explained by the increase in capillary radius. However, the values of CR generated by the gravel bed are very limited. For example, in the extreme case of the porosity of the gravel bed \( \phi = 10\% \) and water contact angle \( \theta = 180^\circ \), the CR values of the gravel bed with particle sizes of 50, 100, 150, and 200 \( \mu \)m are 77.9, 39, 26, and 19.6 kPa, respectively. This additional capillary resistance is too small for the displacement differential pressure to produce appreciable water resistance.

The relationship between the average effective particle size of the gravel bed and CR is presented in Figure 10. The CR decreases sharply with \( d_g \) in the range of 0–40 \( \mu \)m. When \( d_g \) exceeds 40 \( \mu \)m, the capillary resistance declines slowly and finally tends to 0. The capillary resistance is very sensitive to the gravel particle size in the range of 0–40 \( \mu \)m, and even a small increase in gravel particle size can result in a large reduction in capillary resistance. In addition, under a certain
capillary resistance and water contact angle, the larger the porosity is, the smaller the particle size is. Under a certain capillary resistance and porosity, the larger the water contact angle is, the larger the particle size is.

When the porosity of the gravel bed $\phi = 25\%$ and the water contact angle $\theta = 160^\circ$, the curve of the WBC and displacement pressure difference $\Delta p$ with different sizes can be drawn, as shown in Figure 11. Figure 11 shows that with increasing $d_g$, the WBC of gravel bed $\delta$ decreases, and $\delta$ experiences a decreasing trend with an increasing displacement pressure difference. When the $\Delta p$ is 0.5 MPa, the WBCs of the gravel bed with $d_g$ values of 20, 40, 60, and 80 $\mu$m are 0.22, 0.12, 0.08, and 0.06, respectively. When the $\Delta p$ reached up to 1 MPa, the WBCs of the gravel bed with different particle sizes decreased to 0.12, 0.06, 0.04, and 0.03. Only when the $\Delta p$ is less than 1 MPa and $d_g$ is less than 40 $\mu$m can hydrophobic gravel beds show a certain WBC; the smaller $\Delta p$ and $d_g$ are, the stronger the water resistance is.

4.2.3. Effect of Gravel Particle Wettability. The wettability of gravel particles is one of the most important factors in determining the value and direction of capillary force. Here, the water contact angle $\theta$ value of the gravel bed is used to represent the wetting degree of the gravel particle. Obviously, when the water contact angle is less than 90°, the direction of the capillary force generated by the gravel bed points to the wellbore, which is not conducive to water blocking. In contrast, when the water contact angle exceeds 90°, the direction of the capillary force generated by the gravel bed points to the formation, which is conducive to water blocking. When the water phase contact angle is equal to 90°, a capillary force does not exist. Therefore, in this paper, only water contact angles over 90° are discussed. The water contact angles $\theta$ were set as 120, 150, and 180°, and the capillary resistance generated by the gravel bed was calculated. The results are shown in Figures 12 and 13. With an increasing water contact angle, the CR increases, and when the $\phi$ is 15% and the $d_g$ is 10 $\mu$m, the CRs of the gravel bed with $\theta$ values of 120, 150, and 180° are 0.122, 0.212, and 0.244 MPa, respectively.

Ensuring that the porosity of the gravel bed $\phi = 25\%$ and the average particle size of the gravel $d_g = 10 \mu m$, the curve of the WBC and $\Delta p$ with different wettabilities was plotted, as shown in Figure 14. Figure 14 shows that with a decrease in the water contact angle $\theta$ of the gravel bed, the WBC decreases, but the decrease is not significant. When the $\Delta p$ is 0.5 MPa, the WBCs...
of the gravel bed with θ values of 120, 150, and 180° are 0.31, 0.38, and 0.41, respectively. When the Δp increases to 1 MPa, the WBCs of each wettability gravel bed increase to 0.17, 0.21, and 0.23. This result indicates that the wettability of the gravel bed has less influence on WBC than the gravel particle size, but to enhance the WBC of the gravel bed, gravel with strong hydrophobicity should be used as much as possible.

4.2.4. Effect of Gravel Bed Porosity. The compaction degree of the gravel bed is also an important factor affecting the capillary resistance and WBC of the gravel bed. In this paper, the porosity of the gravel bed ϕ is used to characterize the compaction of the gravel bed. Figures 15 and 16 display the CR of the gravel bed with different porosities. As shown in Figure 15, the CR decreases with increasing porosity of the gravel bed and changes with the change in the water contact angle and the average effective particle size of the gravel. When the water contact angle θ = 150° and the average effective particle size of the gravel bed $d_{e} = 10 \mu m$, the CR values generated by the gravel bed with porosities of 15, 30, 45, and 60% are 0.212, 0.087, 0.045, and 0.025 MPa, respectively.

Ensuring that the water contact angle θ = 150° and the average particle size of the gravel $d_{e} = 10 \mu m$, the curves of WBC and Δp with different porosities are drawn in Figure 17. Figure 17 shows that with increasing porosity in the gravel bed, WBC decreases. When the Δp is 0.5 MPa, the WBCs of the gravel bed with porosities of 15, 25, and 35% are 0.64, 0.40, and 0.27, respectively. When the displacement pressure difference increases to 1 MPa, the WBCs of each wettability gravel bed decrease to 0.38, 0.22, and 0.14. Therefore, to make the hydrophobic gravel bed have a certain water resistance effect, the porosity of the gravel bed should be less than 30%, and the greater the compaction degree of the gravel bed is, the better the water resistance effect is.
4.2.5. Field Application. The hydrophobic quartz sands prepared in this paper can be combined with the gravel packing technology to control the production of formation sand and water. Gravel packing is a process used to control sand in oil wells by forcing gravel proppants between the unconsolidated formation and the wellbore to create a relatively high-permeability sand barrier that prevents sand from entering the wellbore. Conventional gravel-packing processes use unmodified quartz sand proppants, which are usually hydrophilic. However, by replacing the proppant with hydrophobic quartz sands, both formation sand and water can be prevented from entering the wellbore, thereby increasing the oil production. A schematic diagram of the application of hydrophobic gravel packing technology in oil wells is shown in Figure 18. The hydrophobic quartz sands are packed in an annular space between the formation and the screen. When both oil and formation water flow to the hydrophobic gravel bed, the water is prevented from penetrating the hydrophobic gravel bed, while the oil can easily penetrate and flow into the wellbore. As a result, the production of water from the oil well is greatly reduced.

The mathematical model developed in this paper can help field engineers to quickly select the corresponding construction parameters. The production differential pressure can be measured with a downhole pressure gauge during production, and the properties of quartz sand proppants can be calculated from this model. For example, if the production pressure difference of an oil well is 1 MPa, the calculation based on the mathematical model above shows that to make the WBC of the hydrophobic gravel bed exceed 20%, the properties of quartz sand proppant must satisfy the following: particle size $d_g < 50 \mu m$, porosity $\phi < 35\%$, and water contact angle $\theta > 150^\circ$.

5. CONCLUSIONS

In this work, hydrophobic quartz sand proppants were prepared for gravel packing technology to alleviate excess water production during development. In addition, a capillary bundle model of the gravel layer was established to analyze the effects of gravel particle size, wettability, porosity, and displacement pressure difference on the CR and WBC of the gravel bed. Based on the experimental and calculation results, the present work can be concluded as follows:

(1) Both the activation index and water contact angle measurements showed that the quartz sand proppants had the best hydrophobicity after treatment with the HMDS solution at a concentration of 0.6%. At the same time, the activation index is 96% and the water contact angle is $151^\circ$.

(2) The model is verified by previous experimental results. The results show that when the displacement pressure difference is less than 2 MPa, the numerical calculation results are in good agreement with the experimental results, which can accurately predict the WBC of the hydrophobic gravel bed and provide theoretical construction parameters for field construction.

(3) The numerical analysis results show that with increasing gravel particle size and porosity, the CR and WBC of the gravel bed decrease. In the range of $90^\circ$–$180^\circ$, with increasing the water contact angle, the CR and WBC generated by the gravel bed increase. In addition, with an increasing displacement pressure difference, the WBC of the gravel bed decreases, and the rate of decrease decreases from fast to slow.

(4) To ensure that the WBC of the hydrophobic gravel bed $\delta > 20\%$, the following conditions must be satisfied: $d_g < 50 \mu m$, $\phi < 35\%$, $\theta > 150^\circ$, and $\Delta p < 1$ MPa.
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**Notes**

The authors declare no competing financial interest.

**ACKNOWLEDGMENTS**

We gratefully acknowledge the financial support of the Natural Science Foundation of Shandong Province (2019GGX103009 and ZR2019MEE101).

**REFERENCES**

(1) Graham, J.; Alfaro, M.; Ferris, G. Compression and strength of dense sand at high pressures and elevated temperatures. *Can. Geotech. J.* 2004, 41, 1206–1212.

(2) Fortin, J.; Schubnel, A.; Guéguen, Y. Elastic wave velocities and permeability evolution during compaction of Bleurswiller sandstone. *Int. J. Rock Mech. Min. Sci.* 2005, 42, 873–889.

(3) Dautrait, J.; Gland, N.; Youssef, S.; Rosenberg, E.; Bekri, S.; Olga, V. Stress-Dependent Directional Permeabilities of Two Analog Reservoir Rocks: A Prospective Study on Contribution of Tomography and Pore Network Models. *SPE Reservoir Eval. Eng.* 2009, 12, 297–310.

(4) Raza, A.; Safari, M.; Gholami, R.; Downey, W. S.; Ganat, T. A. O. A field scale approach to determine compaction-based permeability in unconsolidated reservoirs. *J. Nat. Gas Sci. Eng.* 2019, 68, 102909.

(5) Yan, M.; Deng, J.; Yu, B.; Li, M.; Zhang, B.; Xiao, Q.; Tian, D. Comparative study on sanding characteristics between weakly consolidated sandstones and unconsolidated sandstones. *J. Nat. Gas Sci. Eng.* 2020, 76, 103183.

(6) Huang, W.; Wang, J.; Chen, H.; Yang, J.; Wu, J.; Ma, N.; Meng, Z.; Jing, Y.; Xu, F.; Ning, B.; Zhang, C. Application of multi-wave and multi-component seismic data in the description on shallow-buried unconsolidated sand bodies: Example of block J of the Orinoco heavy oil belt in Venezuela. *J. Pet. Sci. Eng.* 2021, 205, 108786.

(7) Jia, Y.; Cao, W.; Wang, H.; Ma, B. Influence of multiphase carbonate cementsations on the Eocene delta sandstones of the Bohai Bay Basin. *China J. Pet. Sci. Eng.* 2021, 205, 108866.

(8) Osiansy, S. O. In Practical guidelines for predicting sand production. *Nigeria Annual International Conference and Exhibition; Society of Petroleum Engineers*, 2010.

(9) Cui, C.; Li, K.; Yang, T.; Huang, Y.; Cao, Q. Identification and quantitative description of large pore path in unconsolidated sandstone reservoir during the ultra-high water-cut stage. *J. Pet. Sci. Eng.* 2014, 122, 10–17.

(10) Ranjith, P. G.; Perera, M. S. A.; Perera, W. K. G.; Wu, B.; Choi, S. K. Effective parameters for sand production in unconsolidated formations: An experimental study. *J. Pet. Sci. Eng.* 2013, 105, 34–42.

(11) Shi, X.; Zhang, W.; Xu, H.; Yuan, Z.; Jiang, S. Experimental study of hydraulic fracture initiation and propagation in unconsolidated sand with the injection of temporary plugging agent. *J. Pet. Sci. Eng.* 2020, 190, 106813.

(12) Chung, T.; Bae, W.; Nguyen, N. T. B.; Dang, C. T. Q.; Lee, W.; Jung, B. A Review of Polymer Conformance Treatment: A Successful Guideline for Water Control in Mature Fields. *Energy Sources, Part A* 2011, 34, 122–133.

(13) Lea, J. F.; Nickens, H. V. Solving Gas-Well Liquid-Loading Problems. *J. Pet. Technol.* 2004, 56, 30–36.

(14) Coleman, S. B.; Clay, H. B.; McCurdy, D. G.; Lee, H. N. A New Look at Predicting Gas-Well Load-Up. *J. Pet. Technol.* 1991, 43, 329–333.

(15) Guo, B.; Ghahmirad, A.; Xu, C. A systematic approach to predicting liquid loading in gas wells. *SPE Prod. Oper.* 2006, 21, 81–88.

(16) Yusuf, R.; Veeken, C. A. M.; Hu, B. In Investigation of gas well liquid loading with a transient multiphase flow model, *SPE Oil and Gas India Conference and Exhibition; Society of Petroleum Engineers*, 2010.

(17) Zhang, X.; Liu, W.; Yang, L.; Zhou, X.; Yang, P. Experimental Study on Water Shutoff Technology Using In-Situ Ion Precipitation for Gas Reservoirs. *Energies* 2019, 12, 3881.

(18) Zhang, L.; Pu, C.; Cui, S.; Nasir, K.; Liu, Y. Experimental study of a strong adhesive water shutoff agent in fractured low permeability reservoir. *J. Energy Resour. Technol.* 2016, 139, 71–79.

(19) Dai, C.; Yang, Q.; Guo, Q.; Zhao, F. Study and Application of In-depth Water Control Technology for Production Wells. *Pet. Sci. Technol.* 2011, 29, 2568–2577.

(20) Burshtein, L. S. Effect of moisture on the strength and deformability of sandstone. *Soviet Mining* 1969, 5, 573–576.

(21) Hawkins, A. B.; McConnell, B. J. Sensitivity of sandstone strength and deformability to changes in moisture content. *Q. J. Eng. Geol. Hydrogol.* 1992, 25, 115–130.

(22) Vasanheiro, B.; Ván, P. Influence of water content on the strength of rock. *Engineering Geology* 2006, 84, 70–74.

(23) Shakiba, M.; Khamehchi, E.; Fahimifar, A.; Dabirc, B. An experimental investigation of the proportion of mortar components on physical and geomechanical characteristics of unconsolidated artificial reservoir sandstones. *J. Pet. Sci. Eng.* 2020, 189, 107022.

(24) Bautista, J. F.; Taleghani, A. D. Prediction of formation damage at water injection wells due to channelization in unconsolidated formations. *J. Pet. Sci. Eng.* 2018, 164, 1–10.

(25) Zhang, R.; Shi, X.; Zhu, R.; Zhang, C.; Fang, M.; Bo, K.; Feng, J. Critical drawdown pressure of sanding onset for offshore depleted and water cut gas reservoirs: Modeling and application. *J. Nat. Gas Sci. Eng.* 2016, 34, 159–169.

(26) Shahsavari, M. H.; Khamehchi, E.; Fattahpour, V.; Molla довольно, H. Investigation of sand production prediction shortcomings in terms of numerical uncertainties and experimental simplifications. *J. Pet. Sci. Eng.* 2021, 207, 109147.
(27) Ranjith, P. G.; Perera, M. S. A.; Perera, W. K. G.; Choi, S. K.; Yasar, E. Sand production during the extraction of hydrocarbons from geological formations: A review. J. Pet. Sci. Eng. 2014, 124, 72–82.

(28) Bennion, D. B. An overview of formation damage mechanisms causing a reduction in the productivity and injectivity of oil and gas producing formations. J. Can. Pet. Technol. 2002, 41, 29–36.

(29) Tangparitkul, S.; Saul, A.; Leelasukseree, C.; Yusuf, M.; Kalantari, A. Fines migration and permeability decline during reservoir depletion coupled with clay swarming due to low-salinity water injection: An analytical study. J. Pet. Sci. Eng. 2020, 194, 107448.

(30) Sun, X.; Bai, B. Comprehensive review of water shutoff methods for horizontal wells. Petroleum Exploration and Development. 2017, 44, 967–973.

(31) Imqam, A.; Bai, B.; Delshad, M. Micro-particle gel transport performance through unconsolidated sandstone and its blocking to water flow during conformance control treatments. Fuel 2018, 231, 479–488.

(32) Goudarzi, A.; Hao, Z.; Varavei, A.; Taksadom, P.; Hu, Y.; Delshad, M.; Bai, B.; Sepehrnoori, K. A laboratory and simulation study of preformed particle gels for water conformance control. Fuel 2015, 140, 502–513.

(33) Goudarzi, A.; Almohsin, A.; Varavei, A.; Taksadom, P.; Hosseini, Seyed; Bai, B.; Sepehrnoori, K. New laboratory study and transport model implementation of microgels for conformance and mobility control purposes. Fuel 2017, 192, 158–168.

(34) Hatzignatiou, D. G.; Giske, N. H.; Stavland, A. Polymers and Polymer-Based Gels for Improved Oil Recovery and Water Control in Naturally Fractured Chalk Formations. Chem. Eng. Sci. 2018, 187, 302–317.

(35) Zaitoun, A.; Kohler, N.; Montemurro, M. A. In control of water influx in heavy-oil horizontal wells by polymer treatment; SPE Annual Technical Conference and Exhibition: Washington; 1992.

(36) Bai, B.; Huang, F.; Liu, Y.; Seright, R. S.; Wang, Y. In Case study on preformed particle gel for in-depth fluid diversion; SPE Annual Technical Conference and Exhibition: Washington; 2008.

(37) Jin, Z.; Liu, T.; Gu, K. Application of hydrophobic lipophilic proppant in fracturing of oil layer nearby water layer. Fault-Block. Fault-Block Oil & Gas Field. 2012, 19, 93–95.

(38) Yang, J. M.; Yang, J. L. Study on preparation and properties of reservoir fracturing sands coated with super hydrophobic VFM film. J. Qingdao Univ. Sci. Technol., Nat. Sci. Ed. 2011, 32, 67–71.

(39) Tabatabaei, M.; Taleghani, A. D.; Cai, Y.; Santos, L.; Alem, N. Surface modification of proppant using hydrophobic coating to enhance long-term production. SPE Prod. Oper. 2021, 36, 116–127.

(40) Fu, L.; Zhang, G.; Ge, J.; Liao, K.; Meng, Y. Study on a new water-inhibiting and oil-increasing proppant for bottom-water-drive reservoirs. J. Pet. Sci. Eng. 2016, 145, 290–297.

(41) Liu, Y.; Wang, H.; Meng, W.; Zhang, C.; Zhi, J.; Shen, A. Stimulation experiment of horizontal wells filled with permeable and water-blocking gravel in deepsea bottom-water gas reservoirs. Natural Gas Industry B. 2020, 7, 390–396.

(42) Liu, S.; Shan, M.; Wang, J.; Yang, C. A model of capillary tube bundles for tortuous streamtube in unconsolidated porous medium with spherical particles. Mining and Metallurgy. 2007, 16, 39–42.

(43) Wei, B.; Chang, Q.; Bao, C.; Liang, D.; Zhang, G.; Wu, F. Surface modification of filter medium particles with silane coupling agent KH550. Colloids Surf. A 2013, 434, 276–280.

(44) Hou, W.; Zhang, Y.; Liu, T.; Lu, H.; He, L. Graphene oxide coated quartz sand as a high-performance adsorption material in the application of water treatment. RSC Adv. 2015, 5, 8037–8043.

(45) Men, X.; Ge, B.; Li, P.; Zhu, X.; Shi, X.; Zhang, Z. Facile fabrication of superhydrophobic sand: Potential advantages for practical application in oil water separation. J. Taiwan Inst. Chem. Eng. 2016, 60, 651–655.

(46) Liu, P.; Guo, S.; Lian, M.; Li, X.; Zhang, Z. Improving water-injection performance of quartz sand proppant by surface modification with surface-modified nanosilica. Colloids Surf. A 2015, 470, 114–119.

(47) Liu, K.; Zheng, N.; Li, X.; Zhang, Z. Preparation of in-situ surface-modified nanosilica and its application in separating oil from water. Micro Nano Lett. 2013, 8, 15–18.

(48) Zhou, J. P.; Qiu, K. Q.; Fu, W. L. The surface modification of ZnOw and its effect on the mechanical properties of filled polypropylene composites. J. Compos. Mater. 2005, 39, 1931–1941.

(49) Yang, S.; Wei, J. Petrophysics. Beijing: Petroleum Industry Press. 2006, 157–158.

(50) Kozeny, J. Uber kapillare Leitung des Wassers im Boden. Sitzungber Akad. Wiss. Wien. 1927, 136, 271–306.

(51) Carman, P. C. Permeability of saturated sands, soils and clays. J. Agric. Sci. 1939, 29, 262–273.