

## Research Article

# Numerical Simulation Investigation on Well Performance Integrated Stress Sensitivity and Sand Production

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For unconsolidated sanding wells, the interaction between sanding and pressure-dependent permeability as oil is produced from the bottom of the well puts higher challenges on the evaluation and prediction of well performance. Therefore, it is essential to assess the oil well performance considering the synthetic effect of stress-sensitive and produced sand particles. In this paper, a new stress-sensitive factor is proposed to describe the relationship between stress and permeability in the numerical model. Also, based on the rectangular plastic region by the sand migration near the perforation, a quantitative expression of the sanding area for numerical model calculation was established. Combined with a quantitative description of these two key parameters, a sand-producing horizontal well model is established to evaluate production performance. In this model, the area of sand production near the wellbore is considered as the inner area with increased permeability while the outer zone remains the original reservoir. Besides, the model was verified by the production data from the sand-producing horizontal well in the oilfield. Furthermore, sensitivity parameters (such as stress sensitivity, the size of sanding zone, well location, and reservoir boundaries) are used to make the analysis of well productivity, which provides a theoretical basis for petroleum engineers to adjust the development plan for horizontal wells in the weakly consolidated sandstone reservoir.

## 1. Introduction

For unconsolidated sandstone reservoirs, the reduction of pore pressure in the process of crude oil being extracted results in sand migration at the bottom of the wellbore. Besides, stress-dependent permeability is also affected. Therefore, it is a complex problem to evaluate the production performance of stress-sensitive sand-producing wells, which affects the formulation and adjustment of oilfield development schedules.

In the early years, sand control techniques have become a major concern for petroleum engineers in response to sand migration [1–3]. Recently, most of the literature has focused on the prediction of sand production for unconsolidated sandstone reservoirs [4–7]. Besides, laboratory experiments and numerical simulation techniques were also introduced to explore the critical pressure differential for sand production [8, 9]. Furthermore, the mechanism of sand production, the criteria of sand failure, and the key factors affecting sand pro-

duction have gradually attracted the interest of researchers [10, 11]. Generally speaking, for unconsolidated sandstone reservoirs, the previous focus was on the mechanism of produced sands, key factors, and the prediction of sand production. However, there are very few reports about the impact of sand migration on the performance evaluation of oil wells.

Stress sensitivity, as a crucial factor affecting permeability, has been extensively studied in the oil industry, especially in unconventional reservoirs [12–14]. A large number of experimental studies have been carried out to investigate the relationship between pore pressure and permeability. Different factors (e.g., confining pressure, porosity, compressibility, initial permeability) and their combinations are used to establish an expression for permeability [15–18].

In addition, as unconventional oil and gas resources are explored and developed, (semi)analytical solution, numerical simulation techniques are being developed to make the pressure and rate analysis (also known as PTA, RTA) with stress sensitivity [19–21]. However, few models have been reported

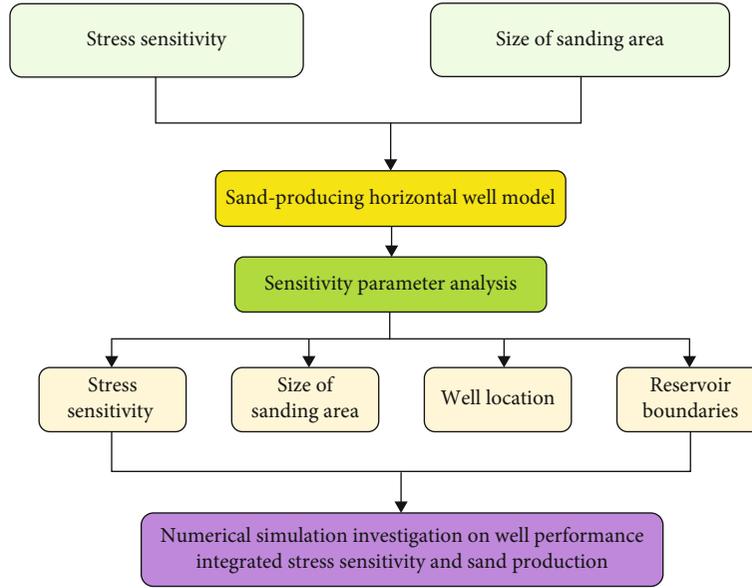


FIGURE 1: Structure diagram of this paper.

considering the synthetical impact of sand migration and stress sensitivity [22–25]. Reference [26] established a bizonal radial composite model considering the effect of stress sensitivity and sand production. Unfortunately, the well performance is not evaluated under such multiple factors.

In this paper, combined with the traditional exponential equation of stress-dependent permeability and the experimental data of stress sensitivity, the quantitative expression of permeability is determined. Then, based on the rectangular plastic zone formed by sand production, the width of sand production was quantitatively characterized. Subsequently, a typical numerical simulation model coupled with a permeability equation and sand area description is established for a sand-producing well in an unconsolidated sandstone reservoir. Due to the decrease of pore pressure during the production process, a sand production area with improved permeability is formed near the bottom hole, which is considered a rectangular composite reservoir with increased permeability in this model. Moreover, the model was validated with production data from an offshore sand-producing horizontal well. And finally, the stress-sensitive effect, the size of sand producing area, the location of the horizontal well, and the reservoir boundary influence on the well performance are also analyzed. The overall structure diagram of this paper is shown in Figure 1.

## 2. Quantitative Characterization of Key Parameters

**2.1. Stress-Dependent Permeability.** During the development of unconsolidated sandstone reservoirs, sand particles migrate near the wellbore as pore pressure decreases, which aggravates the stress sensitivity effect. The stress-dependent permeability characterization formula has been reported [27–29]. Based on the exponential relation of permeability,

as shown in Equation (1), a new stress sensitivity coefficient is introduced in this paper.

$$\frac{K}{K_0} = \beta \left( \frac{\sigma_{\text{eff}}}{\sigma_{\text{eff0}}} \right)^{-\gamma}, \quad (1)$$

where  $\sigma_{\text{eff}}$  is the effective stress of the rock (MPa);  $\sigma_{\text{eff0}}$  is the initial effective stress on the rock (MPa);  $K$  is the rock permeability when the effective stress on the rock is  $\sigma_{\text{eff}}$ ,  $10^{-3} \mu\text{m}^2$ ;  $K_0$  is the rock permeability under the original formation pressure,  $10^{-3} \mu\text{m}^2$ ;  $\beta$  is the coefficient; and  $\gamma$  is the stress sensitivity coefficient defined in this paper. Substituting  $K = K_0$ ,  $\sigma_{\text{eff}} = \sigma_{\text{eff0}}$  into Equation (1),  $\beta = 1$ , the expression of the stress sensitivity coefficient  $\gamma$  can be obtained:

$$\gamma = -\frac{\log(K/K_0)}{\log(\sigma_{\text{eff}}/\sigma_{\text{eff0}})}. \quad (2)$$

The relationship between permeability variations and effective stress with initial permeability can be obtained using Equation (2). In addition, the dynamic change of permeability at any point during the oilfield development can be calculated conveniently, which can be easily used in numerical model calculations. Combined with Equation (2) and permeability under different stress experimental conditions, the stress sensitivity coefficient  $\gamma$  can be obtained. In this paper, for a medium-high permeability sandstone reservoir, the expression of the stress-sensitive coefficient is obtained using the stress-sensitive experimental data of [30], as shown in Figure 2. The stress sensitivity coefficient and the initial permeability show a good linear relationship (as shown in Equation (3)), which can be considered in the numerical model of the produced sand

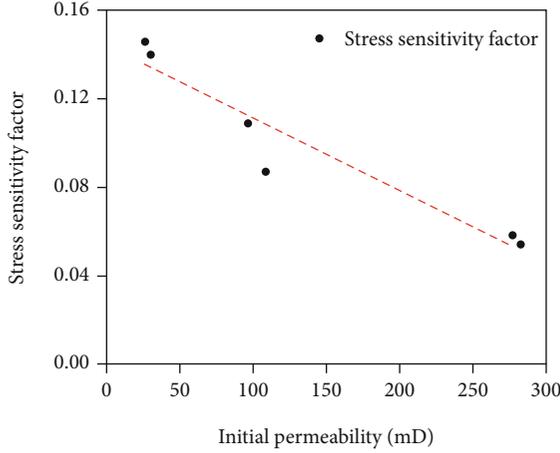


FIGURE 2: Relationship curve between stress sensitivity coefficient and initial permeability.

horizontal well to study the influence of multiple factors on the production performance of oil well.

$$\gamma = aK_0 + b, \quad (3)$$

where  $a$  and  $b$  are constants obtained by experimental fitting,  $a = -0.0003$  and  $b = 0.1437$ .

Therefore, the obtained stress-dependent permeability quantitative relationship can be found in Equation (4). In Equation (4), the permeability considering the stress-sensitive effect can be obtained as long as the initial permeability and the current pressure are given. It is easy to implement in the commercial numerical simulation software tNavigator.

$$K = K_0 \left( \frac{\sigma_{\text{eff}}}{\sigma_{\text{eff0}}} \right)^{-0.0003K_0 + 0.1437}. \quad (4)$$

**2.2. Size of Sand Producing Area.** The determination of the sand-producing area is essential to the establishment of a numerical model for unconsolidated sand-producing wells. In this paper, it is assumed that the horizontal interval is perforated in segments and that sand will be produced in each perforation interval. As a result, the length of the sand-producing zone is slightly longer than the horizontal length. Thus, the key of this model is to determine the width of the sanding zone, that is, the distance it extends forward along the perforation section. Some pieces of literature have reported that the sand-producing area extends forward in a wormhole shape [31]. References [7, 32] considered that the formation after sand production is a plastic zone and extends forward radially, as shown in Figure 3. The sand radius, also known as the width of the sanding zone in this paper, can be roughly calculated by the equal radial stress at the boundary of the elastic plastic stratum. The specific expression is as follows. Combining Equations (5)–(7) and related rock mechanics

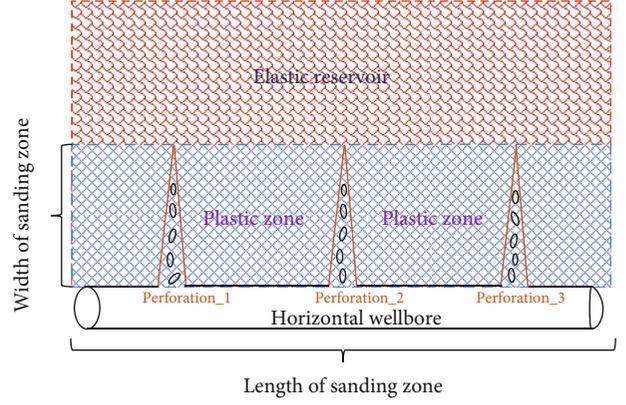


FIGURE 3: Schematic diagram of produced sand in horizontal wellbore.

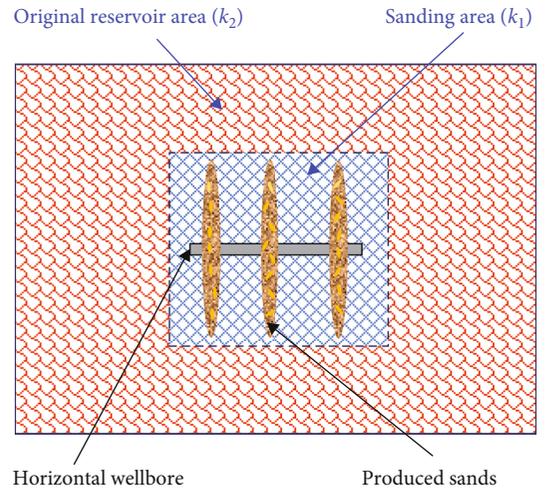


FIGURE 4: Characterization of sand production zones.

parameters and reservoir physical parameters, the width of the sand production area can be determined.

$$c \ln \frac{W_p}{r_w} = \sigma_h - p_{\text{wf}} - \frac{c}{2} + G\alpha \left[ 2I(r_e, t) - \frac{\ln(r_e/r_p)}{\ln(r_e/r_w)} (p_i - p_{\text{wf}}) \right], \quad (5)$$

$$I(r_e) = \int_{r_p}^{r_e} x \left[ \frac{\ln W_p - \ln r_e}{\ln r_e - \ln W_p} (p_i - p_{\text{wf}}) \right] \frac{dx}{r_e^2}, \quad (6)$$

$$\alpha = \frac{3\phi}{3K_B + 4G}, \quad (7)$$

where  $W_p$  is the width of the sanding zone (m);  $c$  is the cohesion of rocks (MPa);  $r_w$  is the radius of the wellbore (m);  $\sigma_h$  is the minimum horizontal stress (MPa);  $p_{\text{wf}}$  is the producing bottomhole pressure (MPa);  $G$  is the shear modulus of rock;  $r_e$  is the drainage radius (m);  $p_i$  is the initial formation pressure (MPa),  $\alpha$  is the shape factor,  $\phi$  is the porosity of the formation, and  $K_B$  is the volume modulus of rock (MPa).

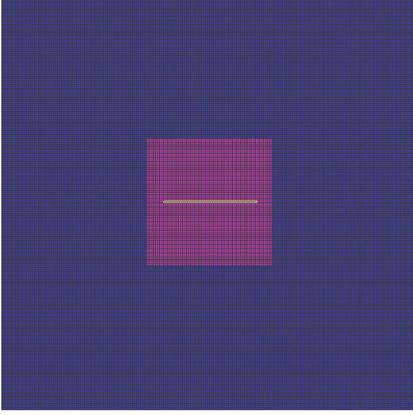


FIGURE 5: Numerical simulation model in this paper.

TABLE 1: Basic parameters of the model.

Basic parameters of the model	Numerical value
Number of grids, each	200 * 200 * 11
Single grid size (m <sup>3</sup> )	10 * 10 * 0.5
Reservoir size (m <sup>3</sup> )	2000 * 2000 * 5.5
Inner area size (m <sup>3</sup> )	600 * 600 * 5.5
Porosity (%)	23
Permeability of outer zone (mD)	150
Inner zone plane permeability (mD)	300
Vertical permeability of inner zone (mD)	30
Original formation pressure (MPa)	14
Fluid density (lb/m <sup>3</sup> )	59.3
Fluid viscosity (mPa·s)	120
Horizontal length (m)	500 (full perforation)
Temperature (F)	176
Wellbore radius (m)	0.1
Bottomhole flowing pressure (MPa)	12
The cohesion of rocks (MPa)	0.1
Minimum horizontal stress (MPa)	12.8
Shear modulus of rocks (MPa)	5000
Volume modulus of rock (MPa)	1200

### 3. Numerical Model of Sand Produced Horizontal Well

**3.1. Physical Model and Assumptions.** It is reported that the decrease in formation pressure during the production process leads to the migration of formation sand particles, forming sand production areas with high permeability channels near the wellbore. Therefore, based on the changes in physical properties and the grid parameter settings in the numerical model, the entire reservoir can be divided into two complex rectangular models (sand production area near the wellbore and unsanding production area in the far well area), as shown in Figure 4.

In this model, the inner zone shown represents the sand production area (with permeability  $k_1$ ). In this paper, the size

TABLE 2: Comparison of example analysis parameters.

Physical variables	Model values	Actual values	
Permeability (mD)	Outer zone	170	
	Inner zone	300	107.4
Horizontal length (m)	Inner vertical	450	450
		23	22.2
Porosity (%)			
Reservoir size (m <sup>3</sup> )	2000 * 2000 * 5.5	—	
Inner area size (m <sup>3</sup> )	600 * 600 * 5.5	—	
Stress sensitive	0.1137		
Fluid density (lb/m <sup>3</sup> )	59.3		
Fluid viscosity (mPa·s)	120		

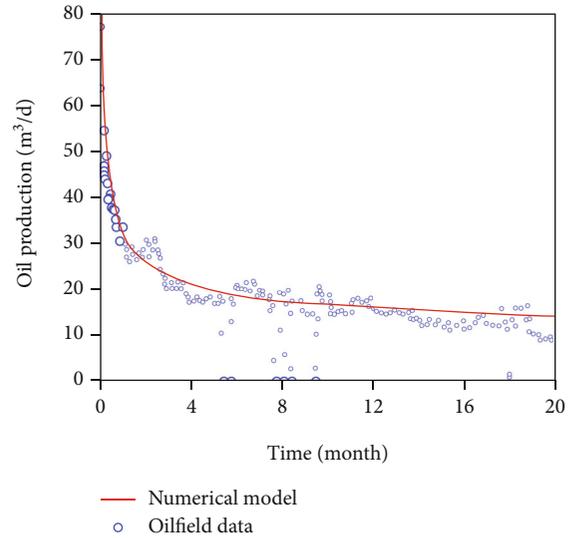


FIGURE 6: Fitting results of an actual produced sand horizontal well.

TABLE 3: The basic parameters of the productivity model considering the stress-sensitive influence.

Physical quantity	Parameter	Value
$K_1$	Permeability of inner zone (mD)	420
$K_2$	Permeability of outer zone (mD)	300
$S$	Skin factor, dimensionless	3
$L$	Horizontal length (m)	500
$L_p$	Length of sanding area (m)	600
$W_p$	Width of sanding area (m)	600
$\gamma$	Stress sensitivity coefficient	0.02

of the sand production area is determined by the length of the horizontal well. The outer area in red represents the original reservoir (permeability  $k_2$ ), which is not affected by the sand production area. The produced sands may contribute to an increase in permeability, which can be found in the study of [31]. Therefore, the permeability of the sand producing area

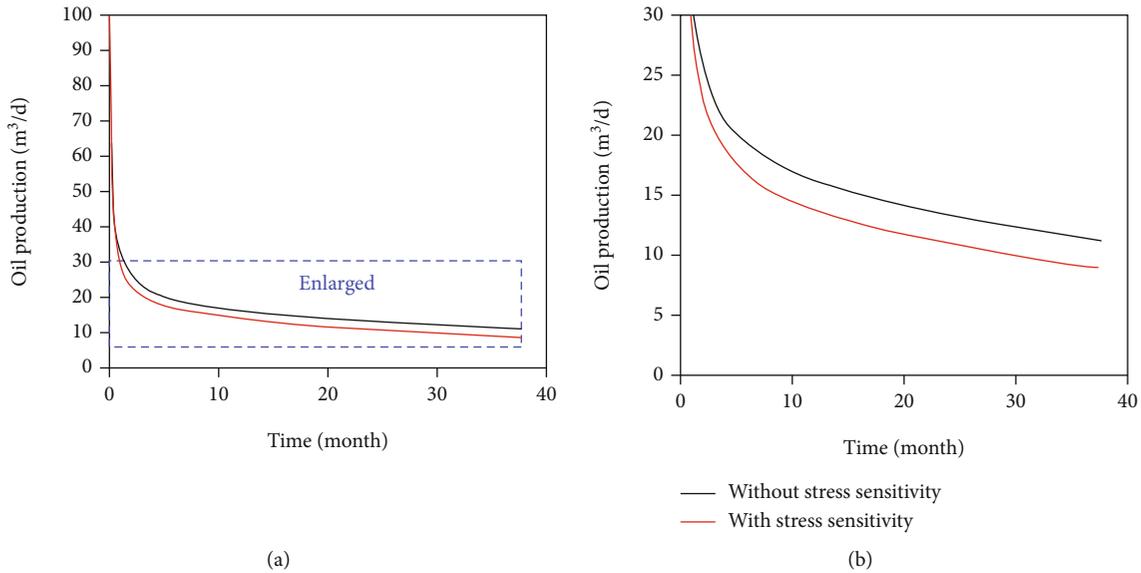


FIGURE 7: Influence of stress sensitivity.

( $k_1$ ) in this model is greater than that of the original reservoir ( $k_2$ ). Moreover, the assumptions of this numerical model are as follows:

- (1) This weakly consolidated sandstone reservoir is simplified into a cubic two-zone model, and multiple factors such as stress sensitivity, heavy oil, and sand migration are considered
- (2) In this numerical model, all sides of the reservoir are closed with the initial formation pressure  $p_i$
- (3) The numerical model only considers the sand production area formed by sand migration and does not consider the dynamic changes of the sand production process
- (4) Considering the sand migration in the range of the horizontal wellbore, therefore, the length of the sand production area is slightly longer than the horizontal length

**3.2. Model Parameters.** In this numerical model, due to the sand particle migration of the weakly consolidated sandstone, we consider that there is a stress-sensitive effect in the whole area. The stress sensitivity coefficient of each zone can be determined by the quantitative relationship with the initial permeability (Equation (4)). Based on the quantitative characterization relationship between permeability (Equation (4)) and sanding width (Equation (5)), a numerical model of the horizontal sanding well with stress sensitivity in the weakly consolidated formation is established using the commercial numerical simulation software tNavigator, as shown in Figure 5. This numerical simulation model is mainly aimed at horizontal sanding well, and the production variations under multiple factors of stress sensitivity and produced sands are investigated. This model sets a grid size of  $10 * 10 * 0.5 \text{ m}^3$  to simulate the reservoir. The horizontal

section length is 500 m, the corresponding sand production area is  $600 * 600 * 5.5 \text{ m}^3$ , the initial permeability is 150 mD, the inner permeability is 300 mD, the original formation pressure is 14 MPa, and considering the crude oil viscosity is 120 mPa·s. More details of the model parameters are shown in Table 1. The related rock mechanics parameters (such as rock cohesion, shear modulus) are used to calculate the width of the sand zone.

**3.3. Model Verification.** Based on the numerical model established above, a heavy oil sand production well in a certain offshore weakly consolidated sandstone reservoir in China is used as an example to analyze the actual production data and the production data of the model through the history matching technology to compare and verify the actual production data. The sand-producing horizontal well has medium and high permeability ( $K = 107 \text{ mD}$ ,  $\varphi = 0.22$ ), the bottom of the well shows sand migration, and the length of the horizontal well is 450 m. In order to fit the production performance, fine-tuning was made based on the existing well parameters. The comparison between model parameters and actual well parameters is shown in Table 2. The fitting results obtained are shown in Figure 6.

It can be seen from Figure 4 and Table 2 that the numerical model can better fit the production data with the average relative error of 0.35, which proves that this model is accurate and can be used to analyze oil well production performance.

## 4. Results and Discussion

Based on the reliable two-zone model of sand-produced horizontal well established above, the effects of stress sensitivity, sanding area, and positions of horizontal well and boundaries on oil production are analyzed, and the results are as follows.

**4.1. Stress Sensitivity.** In order to analyze the impact of stress sensitivity on oil production, the model setting parameters

TABLE 4: The basic parameters of the capacity model considering the influence of the partition size.

Physical quantity	Parameter	Value
$K_1$	Permeability of inner zone (mD)	420
$K_2$	Permeability of outer zone (mD)	300
$S$	Skin factor, well completion method dimensionless	3
$L$	Horizontal length (m)	500
$L_p$	Length of sanding area (m)	560
$W_p$	Width of sanding area (m)	100~900
$\gamma$	Stress sensitivity coefficient dimensionless	0.02

are shown in Table 3 below, and the corresponding results are shown in Figure 7. Figure 7(a) is enlarged to better compare the differences between the curves, as shown in Figure 7(b). As can be seen from Figure 7, the production curve presents a trend of “continuous decline,” with a sharp decline in the early stage and a steady decline in the later stage. Figure 7(b) shows that the daily production with stress sensitivity is lower than the daily production without stress sensitivity. It indicates that stress sensitivity will reduce the daily production of oil wells. And it can be seen that the impact of stress sensitivity on daily oil production is mainly manifested in the middle and late production stages.

**4.2. Size of Sanding Area.** The effect of the produced sand size on oil production is also investigated in this paper. Generally, sand particles migrate near the screen and form a sand-producing area. In this model, variable width (100~900 m) is considered to simulate the effect of different sand-producing area sizes on oil well production. The details of other related parameters can be found in Table 4, and the corresponding results obtained are shown in Figure 8.

- The larger the sand-producing area, the more the high-permeability channels in the reservoir, and the higher the stable production during the later period
- There is a significant enhancement of oil production as the width of the sanding zone is increased from 100 m to 500 m. When it exceeds 500 m, oil production stops increasing. Thus, it is a critical value for the contribution of the produced sand size to oil production, which also theoretically explains the significance of moderate sand control technology for sand-producing wells

**4.3. Location of Horizontal Well and Boundaries.** In this paper, the effects of different locations of horizontal wells and reservoir boundaries are considered to make the analysis of production curves.

**4.3.1. Well Location.** In this article, it is assumed that the reservoir boundary is closed to analyze the effects of different well locations. The influence of the distance between the well and the closed boundary (30 m, 200 m, 1000 m) on the well

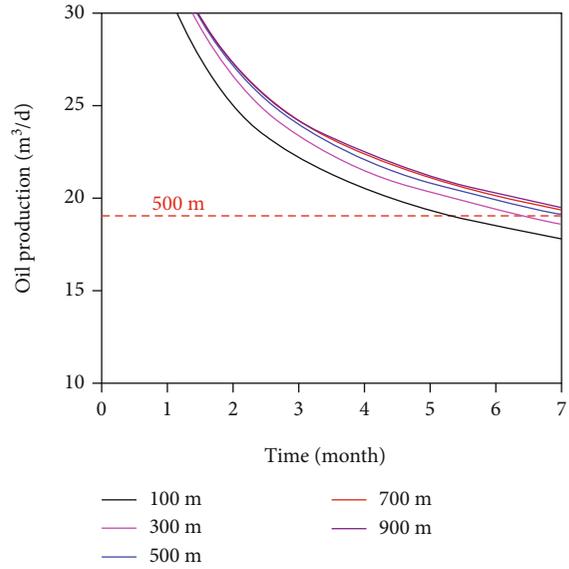


FIGURE 8: The effect of sanding size on oil production.

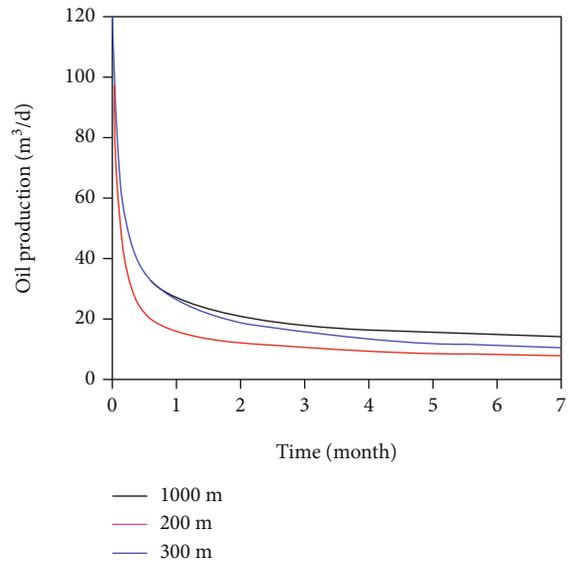
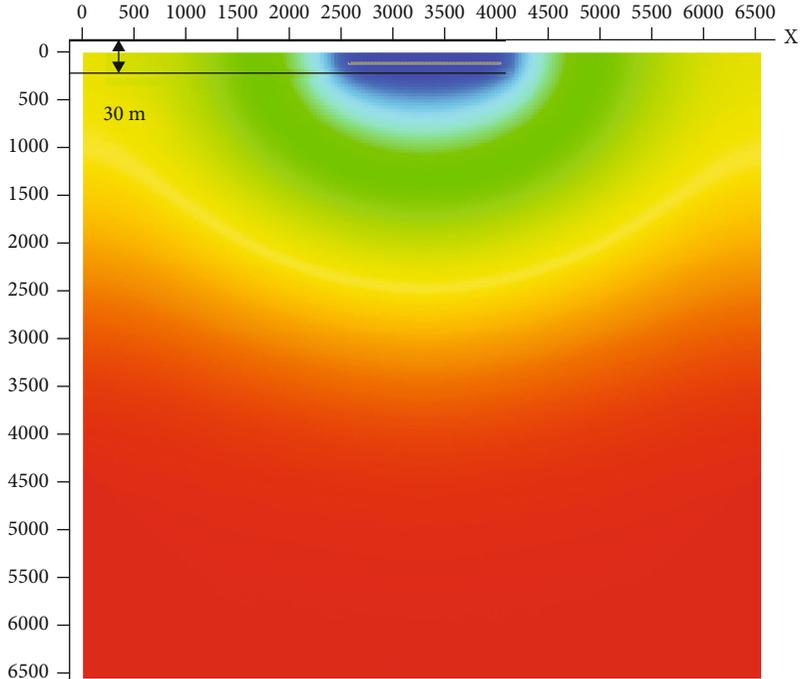


FIGURE 9: The effect of well position on oil production.

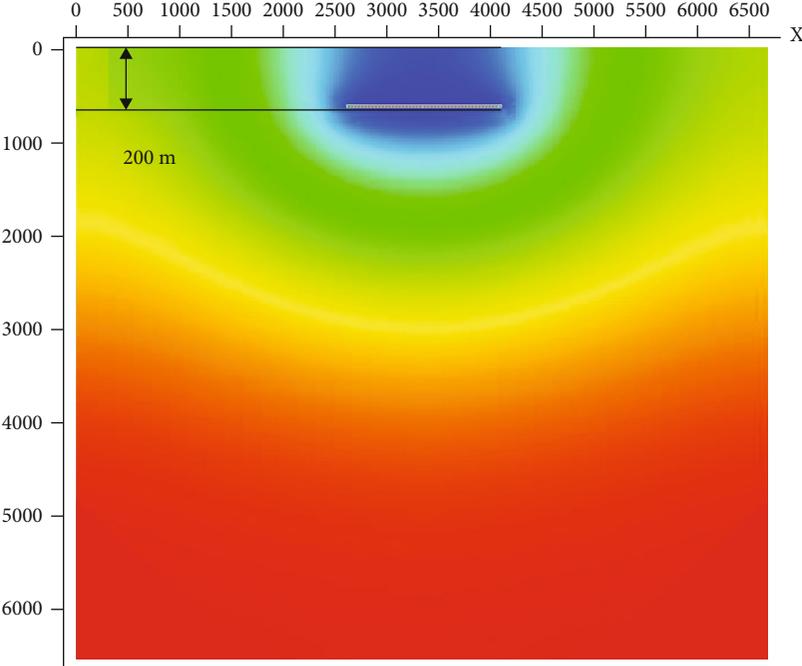
productivity is analyzed, and the results obtained are shown in Figure 9, which shows the following:

- The closer the production well is to the closed boundary, the faster the production decline, the lowest the production in a short period of time, and the lower the stable production in the later period
- The position of the production well from the closed boundary mainly affects the shape of the decline curve. When it is far from the closed boundary (200 m~1000 m), the productivity curve shows a gentle downward trend

The pressure profiles at different positions are shown in Figure 10. It can be seen that the closer the production well



(a) 30 m



(b) 200 m

FIGURE 10: Continued.

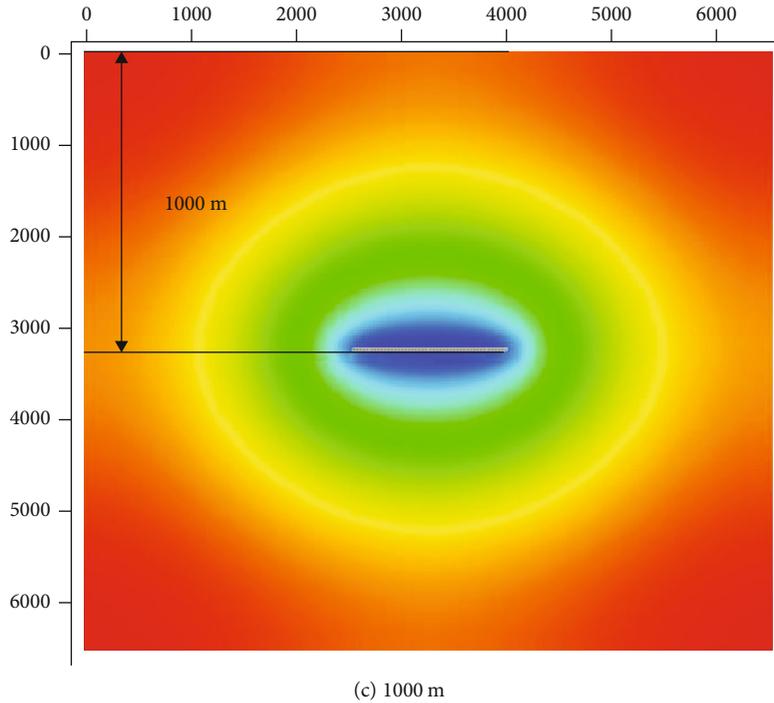


FIGURE 10: Pressure field diagrams of different well positions (1000 m, 200 m, 30 m).

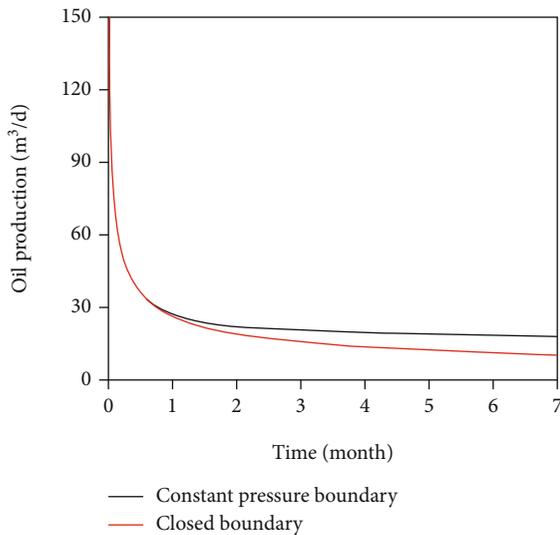


FIGURE 11: The influence of different boundary conditions on production.

is to the closed boundary, the smaller the area affected by the formation pressure is. When the well is only 30 m away from the closed boundary, the oil in the lower part of the reservoir is difficult to be produced.

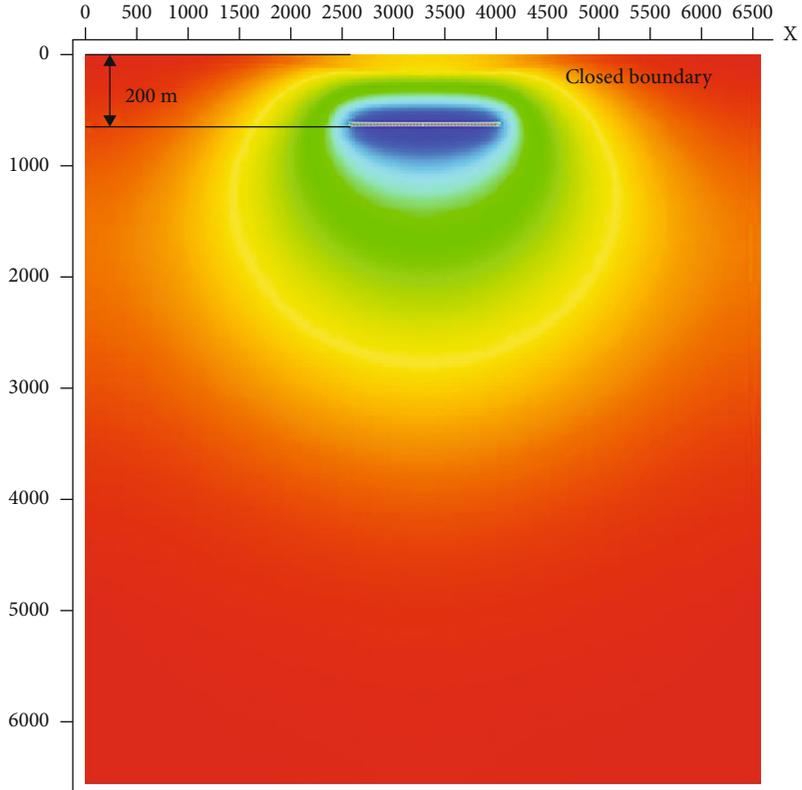
**4.3.2. Reservoir Boundaries.** As mentioned above, a horizontal well 200 m away from the closed boundary is taken as a contrast to analyze the influence of different boundaries on well performance, as shown in Figure 11. The pressure profiles under different boundary conditions are shown in Figure 12.

It can be seen from Figures 11 and 12 that the distinction of the closed boundary and the constant pressure boundary on the production of the sanding well is mainly manifested after one month of production. It is attributed to the fact that the oil well has been replenished with sufficient energy during production at the constant pressure boundary conditions and has maintained a relatively high and stable production rate. On the contrary, the horizontal well with a closed boundary is less productive as pressure propagates to the boundary due to the lack of timely energy supplement.

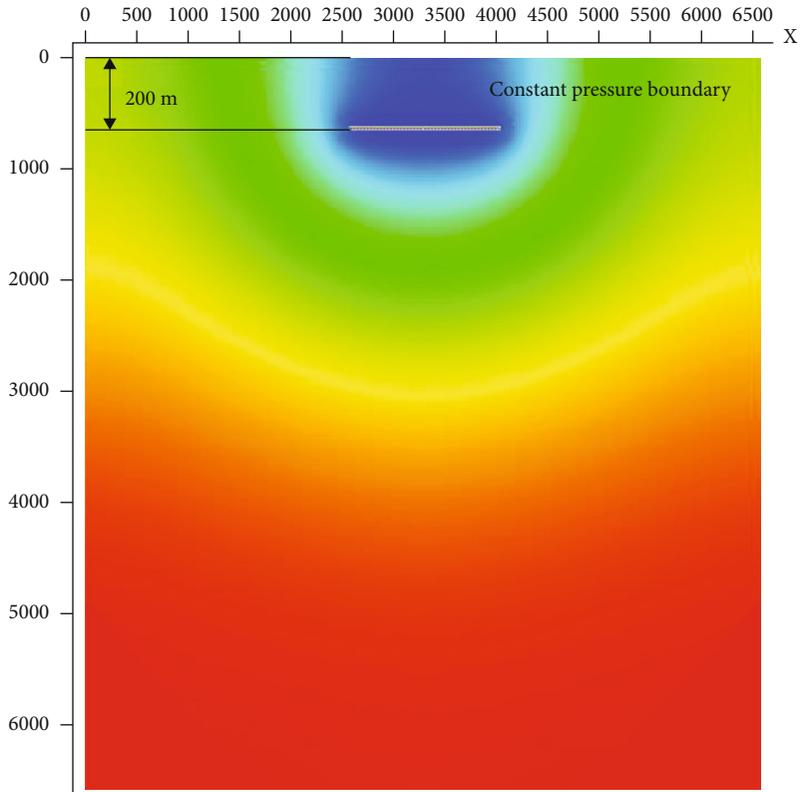
## 5. Conclusion

In this paper, the numerical model of a horizontal well with produced sand is established to analyze the influence of sensitivity parameters on well performance, and the following conclusions are drawn:

- (1) The trend of a sharp decline in the early stage and a steady decline in the later stage is reflected in the production curve. Also, stress sensitivity can reduce daily oil production, which is mainly reflected in the middle and late stages of production
- (2) The augment of sand-producing areas provides more channels for oil flow; thus, it will increase oil production. However, there is also a critical size of the sand production zone to the contribution of oil production, which is further evidence of the possibility of moderate-produced sand techniques
- (3) The location of the production well from the closed boundary mainly affects the shape of the decline curve. When it is far from the closed boundary



(a) Closed boundary



(b) Constant pressure boundary

FIGURE 12: Pressure distribution with different boundary conditions.

(200 m~1000 m), the productivity curve shows a gentle downward trend

- (4) The energy depletion of the constant pressure boundary is slower, and the later production is higher and stable, since the oil well with closed boundary has a relatively lower production without the timely energy supplement

## Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

## Conflicts of Interest

No conflict of interest exists in the submission of this manuscript.

## Authors' Contributions

The manuscript is approved by all authors for publication.

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