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Sand Production Analysis for Depleted Reservoir

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Abstract

For most oilfields, the later development stage will be after long time production, and pore pressure is seriously depleted. The in situ stress of reservoir will be affected, and the stress state will be changed, so that to cause sand production. Based on Hooke's law, the theoretical formula of two horizontal stress changes is obtained, and the stress distribution is established. The model of critical down-hole pressure for sand production in depleted reservoir is established. Based on the model, the influence of pressure depletion on critical drawdown pressure is analyzed for sand production. The results show that: with the pore pressure decreasing, the horizontal in situ stress and critical drawdown pressure decrease; Dynamic stress distribution is obtained with the pressure depletion in the development process, but the critical drawdown pressure decreasing rate with reservoir pressure depletion is less than the pore pressure. The critical drawdown pressure based on Mogi-Coulomb criterion is the most accurate, but that based on Mohr-Coulomb criterion is the most safety.

Key words: Pressure depletion; Sand production; Critical drawdown pressure

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INTRODUCTION

For Conventional oil and gas reservoirs, extensive research on sand production has been done[1]. For the mechanism of sand production, some models are based on mixed hydro mechanical process, and some others are based on mechanical stability[2-4]. Generally, sand production for brittle rock just result from mechanical failure. With the reservoir development, the reservoir pressure will deplete, the risk of sand production will increase[5-6]. Some research for sand production of depleted reservoir has been down, but in the research the influence of pressure depletion on in situ stress hadn't been considered. Mostly, Mohr-Coulomb criterion and Drucker-Prager criterion are used for sand prediction. But Mohr-Coulomb criterion is conservative while Drucker-Prager criterion tends to be unsafe Mogi-Coulomb criterion has been proved more suitable for evaluate borehole breakout[7-8]. So in this paper, some analysis about the effect of pressure depletion on in situ stress and critical down-hole pressure model will be developed.

1. THE EFFECT OF PRESSURE DEPLETION ON IN-SITU STRESS

The overburden pressure comes from the weight of the formation above, so the reservoir pressure depletion has no effect on the overburden pressure. But for the reservoir with flat geologic structure and thin formation, there is a little difference in porous elastic properties with surrounding rock. Due to the deformation of formation in horizontal plane caused by pressure depletion is almost negligible, the reservoir is approximately with no horizontal deformation, i.e:

$$\Delta\varepsilon_h=\Delta\varepsilon_H=0 \quad (1)$$

Where $\Delta\varepsilon_h$, $\Delta\varepsilon_H$ are the strain caused by pressure depletion in the maximum horizontal in situ stress direction and minimum horizontal in situ stress direction respectively. According to the generalized Howk's law, the reservoir constitutive relationship before the oilfield is developed is as follows:

$$\begin{cases} \varepsilon_v = \dfrac{1}{E}\left[\sigma_v - \alpha Pp - \mu(\sigma_h - \alpha Pp + \sigma_H - \alpha Pp)\right] \\ \varepsilon_H = \dfrac{1}{E}\left[\sigma_H - \alpha Pp - \mu(\sigma_v - \alpha Pp + \sigma_h - \alpha Pp)\right] \\ \varepsilon_h = \dfrac{1}{E}\left[\sigma_h - \alpha Pp - \mu(\sigma_v - \alpha Pp + \sigma_H - \alpha Pp)\right] \end{cases} \quad (2)$$

Where E is the Young's modulus, GPa; μ is the Passion's ratio; σ_H and σ_h are the maximum and minimum horizontal in situ stress, MPa, respectively; σ_v is the overburden pressure, MPa; P_p is the original pore pressure, MPa; a is effective stress coefficient.

When the pore pressure depletes to P_{p1}, MPa, and no changes with the overburden pressure, the constitutive relationship in horizontal direction as followings:

$$\begin{cases} \varepsilon_{H1} = \dfrac{1}{E}\left[\sigma_{H1} - \alpha P_{p1} - \mu(\sigma_v - \alpha P_{p1} + \sigma_h - \alpha P_{p1})\right] \\ \varepsilon_{h1} = \dfrac{1}{E}\left[\sigma_{h1} - \alpha P_{p1} - \mu(\sigma_v - \alpha P_{p1} + \sigma_H - \alpha P_{p1})\right] \end{cases} \quad (3)$$

$$\begin{cases} \varepsilon_{H1} = \varepsilon_H \\ \varepsilon_{h1} = \varepsilon_h \end{cases} \quad (4)$$

$$\begin{cases} \sigma_{H1} = \sigma_H + \dfrac{1-2\mu}{1-\mu}\alpha(P_{p1} - P_p) \\ \sigma_{h1} = \sigma_h + \dfrac{1-2\mu}{1-\mu}\alpha(P_{p1} - P_p) \end{cases} \quad (5)$$

1.1 Borehole Stress Analysis

After drilling, rock is replaced by fluid pressure that provides support, so the stress around the borehole will be redistributed. Assuming the rock around wellbore is porous elastic medium, the stress distribution can be obtained. The borehole effective stress for a vertical well is as follows:

$$\begin{cases} \sigma_r^{'} = p_{wf} - \alpha p_{wf} \\ \sigma_\theta^{'} = (1 - 2\cos 2\theta)\left[\sigma_H + \dfrac{1-2\mu}{1-\mu}\alpha\left(p_{p1} - p_p\right)\right] + \\ \sigma_z^{'} = \sigma_v - 2\mu\left(\sigma_H - \sigma_h\right)\cos 2\theta - \alpha p_{wf} \end{cases}$$

$$(1 + 2\cos 2\theta)\left[\sigma_h + \frac{1-2\mu}{1-\mu}\alpha\left(p_{p1} - p_p\right)\right] - p_{wf} - \alpha p_{wf} \quad (6)$$

While producing, formation fluid flows into downhole, and the additional stress induced by seepage on the borehole wall is as follows:

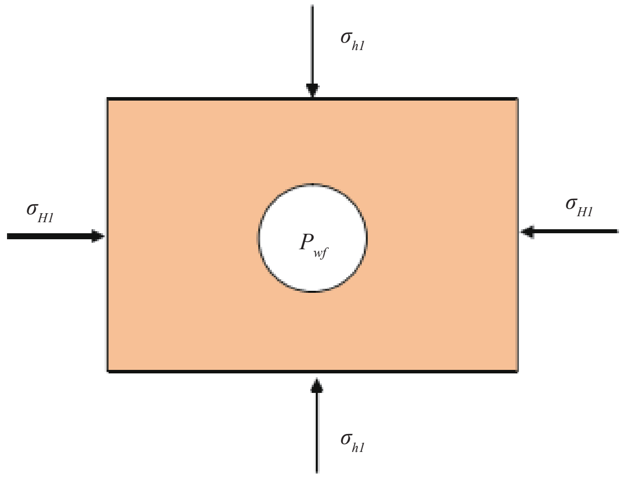


Figure1
Mechanical Model of a Vertical Well

$$\begin{cases} \sigma_{r1} = -f\left(p_{wf} - p_{p1}\right) \\ \sigma_{\theta 1} = \left[\dfrac{\alpha(1-2\mu)}{1-\mu} - f\right]\left(p_{wf} - p_{p1}\right) \\ \sigma_{z1} = \left[\dfrac{\alpha(1-2\mu)}{1-\mu} - f\right]\left(p_{wf} - p_{p1}\right) \end{cases} \quad (7)$$

σ_{r1}, $\sigma_{\theta 1}$, σ_{z1} are radial, tangential, axial stress caused by seepage respectively, Mpa; f is reservoir porosity.

With the reservoir pressure's deplete to P_{p1}, the effective stress for a vertical well is as follows:

$$\begin{cases} \sigma_r^{'} = p_{wf} - \alpha p_{wf} - f(p_{wf} - p_{p1}) \\ \sigma_\theta^{'} = (1 - 2\cos 2\theta)\left[\sigma_H + \dfrac{1-2\mu}{1-\mu}\alpha\left(p_{p1} - p_p\right)\right] + (1 + 2\cos 2\theta)\left[\sigma_h + \dfrac{1-2\mu}{1-\mu}\alpha\left(p_{p1} - p_p\right)\right] - p_{wf} - \alpha p_{wf} \\ \quad + \left[\dfrac{\alpha(1-2\mu)}{1-\mu} - f\right]\left(p_{p1} - p_{p1}\right) \\ \sigma_z^{'} = \sigma_v - 2\mu\left(\sigma_H - \sigma_h\right)\cos 2\theta - \alpha p_{wf} + \left[\dfrac{\alpha(1-2\mu)}{1-\mu} - f\right]\left(p_{p1} - p_{p1}\right) \end{cases} \quad (8)$$

1.2 Critical Downhole Pressure Prediction

Generally, the rock's strength will decrease after the formation failure, that causes sand production[8]. In this paper, Mohr-Coulomb criterion, Drucker-Prager criterion and Mogi-Coulomb criterion are selected to calculate critical downhole pressure.

1.3 Based on the Mohr-Coulomb Criterion

The Mohr-Coulumb criterion can be expressed as following:

$$\sigma_1 - \alpha p = \left(\sigma_3 - \alpha p\right)\tan^2\left(\frac{\pi}{4} + \frac{\phi}{2}\right) + 2C\tan\left(\frac{\pi}{4} + \frac{\phi}{2}\right) \quad (9)$$

Where σ_1 and σ_3 are the maximum and minimum principal stress, respectively, Mpa; ϕ is the internal friction angle; C is the cohesion force, Mpa; P is the pore pressure, Mpa.

The stress state changes with the formation pressure change, and in the depletion process, the critical downhole pressure changes with the pore pressure. When the formation pressure depletes from P_p to P_{p1}, the critical downhole pressure can be expressed as:

$$p_{wf} = \frac{3\sigma_H - \sigma_h + (3\zeta - f)p_{p1} - 2\zeta p_p - 2CK - fK^2}{(1 - f - \alpha)K^2 - \zeta + f + \alpha + 1} \quad (10)$$

$$\zeta = \alpha(1 - 2\mu)/(1 - \mu) \quad (11)$$

$$K = \tan(45^0 + \frac{\phi}{2}) \quad (12)$$

1.4 Based on the Drucker-Prager Criterion

The Drucker-Prager criterion expression is as follows:

$$\sqrt{J_2} = K_f + RI_1 \quad (13)$$

$$J_2 = \frac{1}{6}\left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\right] \quad (14)$$

$$I_1 = \sigma_1 + \sigma_2 + \sigma_3 - 3\alpha p \quad (15)$$

Where I_1 is the first stress tensor invariant; J_2 is the second stress tensor invariant; K_f and R are both rock strength parameters.

The critical downhole pressure is as follows:

$$p_{wf} = \frac{-M - \sqrt{M^2 - 4FN}}{2F} \quad (16)$$

$$\begin{aligned} F &= \zeta^2 - \zeta + 3 - 3R^2(2\zeta - 3\alpha)^2 \\ M &= \zeta(A+B) - 3A - 6R(K_f + RA + RB)(2\zeta - 3\alpha) \\ N &= A^2 + B^2 - AB - 3(K_f + RA + RB)^2 \\ A &= 3\sigma_H - \sigma_h - \zeta p_{p1} \\ B &= \sigma_v + 2\mu(\sigma_H - \sigma_h) - \zeta p_{p1} \end{aligned} \quad (17)$$

1.5 Based on the Mogi-Coulumb Criterion

The octahedral shear stress introduced by Mogi is as follows:

$$\tau_{oct} = f(\sigma_{m,2}) \quad (18)$$

Where τ_{oct} and $\sigma_{m,2}$ are octahedral shear stress and effective intermediate principal stress, respectively, their expressions are as follows:

$$\tau_{oct} = \frac{1}{3}\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2} \quad (19)$$

$$\sigma_{m,2} = \frac{\sigma_1 + \sigma_3}{2} - \alpha p \quad (20)$$

The linear form of Mogi-Coulomb strength criterion is:

$$\tau_{oct} = m + q\sigma_{m,2} \quad (21)$$

$$m = \frac{2\sqrt{2}}{3} C\cos\phi \quad (22)$$

$$q = \frac{2\sqrt{2}}{3}\sin\phi \quad (23)$$

Where m and q are rock strength parameters. The critical downhole pressure is:

$$p_{wf} \frac{-D - \sqrt{D^2 - 4CE}}{2C} \quad (24)$$

$$\begin{aligned} C &= 2\zeta^2 - 6\zeta + 6 - 9q^2(\zeta - 2\alpha)/4 \\ D &= 2\zeta(A+B) - 6A - 9(\zeta - 2\alpha)(2mq + q^2A)/2 \\ E &= 2(A^2 + B^2 - AB) - 9(2m + qA)^2/4 \\ A &= 3\sigma_H - \sigma_h - \zeta p_{p1} \\ B &= \sigma_v + 2\mu(\sigma_H - \sigma_h) - \zeta p_{p1} \end{aligned} \quad (25)$$

2. ANALYSIS

When the downhole pressure is less than the critical downhole flowing pressure, sand production will occur. The critical drawdown pressure is:

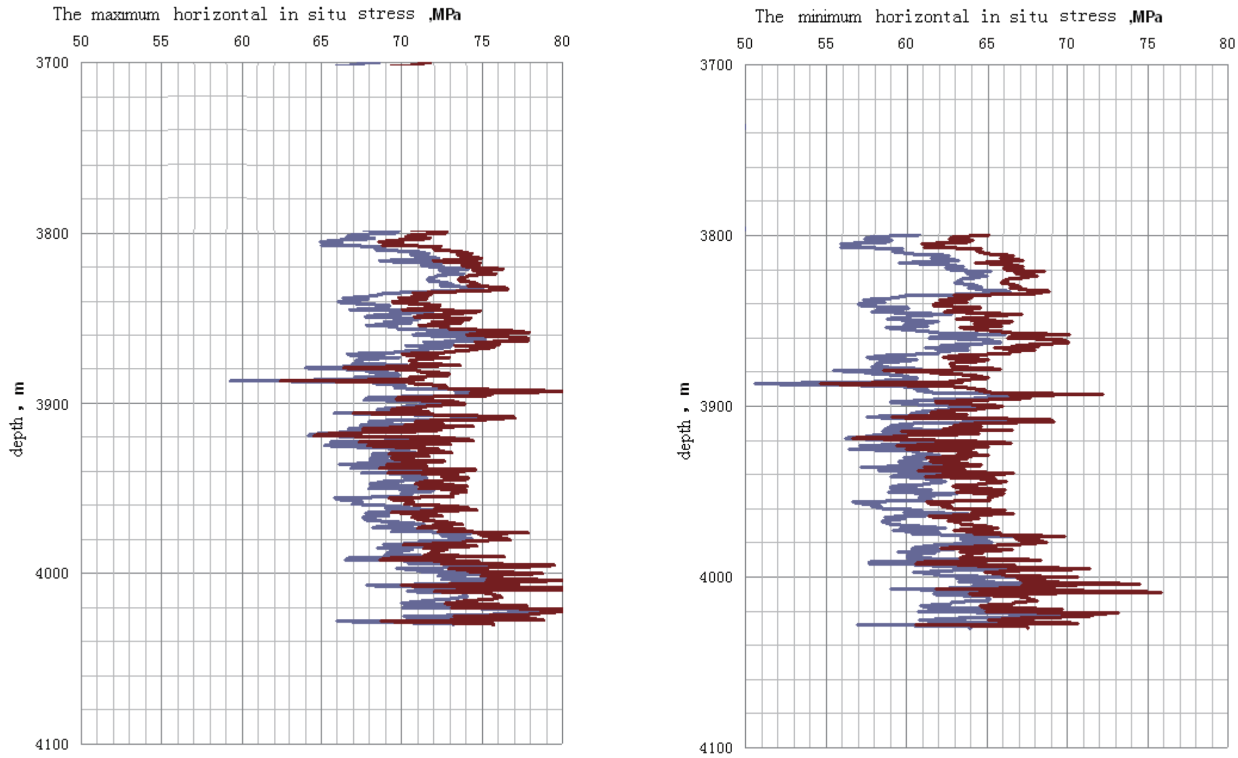
$$\Delta p = p_{p1} - p_{wf} \quad (26)$$

Based on the three models, the change law of critical drawdown pressure was calculated .But in fact, the change of in situ stress because the decrease of formation pressure is the essential reason. To analysis the sand production, the first step is to analyze the change of in situ stress. The parameters are shown in Table 1, and the in situ calculation results are shown in Figure 2, the critical drawdown pressure calculation results are shown in Figure 3.

Table 1
Parameters for Calculation

σ_v (MPa)	σ_H (MPa)	σ_h (MPa)	μ	α	f	ϕ (^{o})	C (MPa)
44	32.85	24.6	0.22	0.8	0.21	28	6
44	30.85	22.60	0.22	0.8	0.21	28	6
44	28.85	20.60	0.22	0.8	0.21	28	6
44	26.85	18.60	0.22	0.8	0.21	28	6
44	24.85	16.60	0.22	0.8	0.21	28	6

As can be seen from Figure 2, the blue line is the in situ stress after depletion, and the red line are the in situ stress before depletion. The in situ stress after depletion is much lower than before. As can be seen from figure 3, the critical drawdown pressure deceases and the risk of sand production increases with the formation pressure decreases. In the whole production process, the critical drawdown pressure based on Drucker-Prager criterion is always the maximum, and that based on Mogi-Coulomb criterion is less, and that base on the Mohr-Coulomb criterion is the minimum. As can be seen that in the production process of depleted oilfield, it is impossible to keep the production drawdown pressure or bottom hole flowing pressure constant.



(a) Change of the maximum horizontal in situ stress (b) Change of the maximum horizontal in situ stress

Figure 2
Change of in Situ Stress Caused by Depletion

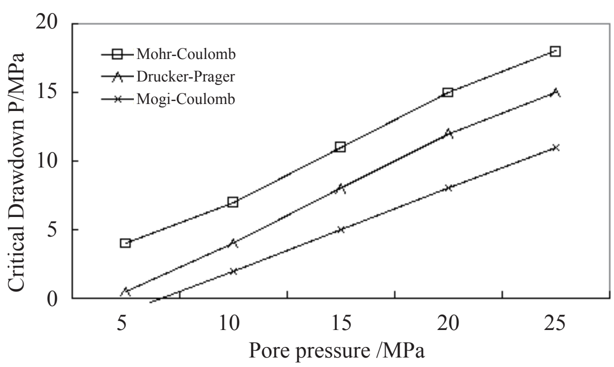


Figure 3
Variation of Critical Drawdown Pressure With Reservoir Pressure

Based on Mohr-Coulomb criterion, the critical drawdown pressure will be 0 when the formation pressure decreases to 5.5 MPa, but based on Mogi-Coulomb criterion and Drucker-Prager criterion, the critical drawdown pressure decreases to zero gradually. So at this time, no matter how much the drawdown pressure is, sand production will occur. Even the strength of consolidated sandstone is high, when the reservoir pressure decreases to a certain extent, sand production may be occur. Figure 4 is risk analysis of sand production for deferent angle and azimuth of deviation well. As can be seen that, the horizontal well with azimuth angle N75E has the maximum risk of sand production, while the vertical well has the minimum risk.

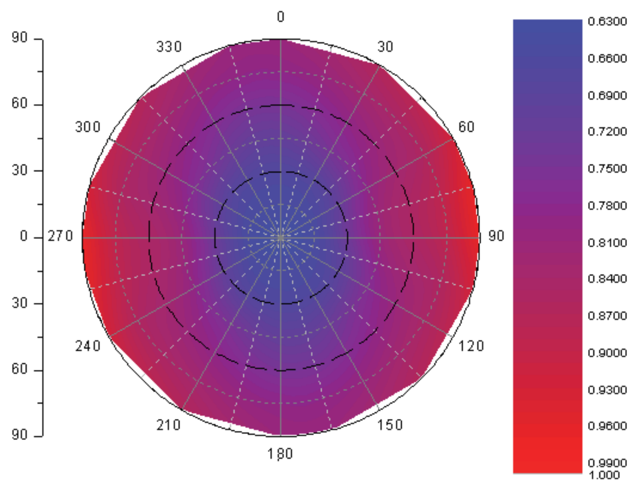


Figure 4
Risk Analysis of Sand Production for Deferent Angle and Azimuth of Deviation

CONCLUSIONS

a. The dynamic stress distribution near borehole is derived and the critical downhole flowing pressure calculation models are established for the pressure depleted reservoir in the development process.

b. The critical drawdown pressure based on Drucker-Prager criterion is the maximum, and that based on Mogi-Coulomb criterion is less, and that based on Mohr-Coulomb criterion is the minimum.

c. The reservoir pressure depletion will lead to critical drawdown pressure decrease, but the decreasing rate is less than the pore pressure.

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