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SAND PRODUCTION PREDICTION IN PRESSURE DEPLETED RESERVOIRS

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ПРОГНОЗУВАННЯ ВИНОСУ ПІСКУ У ВИСНАЖЕНИХ РОДОВИЩАХ

Most oilfields have entered the later development stage, and the pore pressure is seriously depleted. Pressure depletion influences the in-situ stress of the reservoirs and changes the stress state around the boreholes, as well as affects rock strength by causing the compaction of the formation and reducing the porosity of the formation. These two factors synergistically exert influences on the critical drawdown pressure of sand production. Based on the generalized Hoek's law, the theoretical formula representing the change of two horizontal stresses with pore pressure is obtained. The formula was used to analyze the stress distribution around the boreholes in pressure depleted reservoirs. Moreover, exploring the relationship of pore pressure depletion with variation of rock strength and in-situ stress, the model for calculating the critical bottom hole flowing pressure in pressure depleted reservoirs was constructed. The formula was used to analyze the influence of pressure depletion on the critical drawdown pressure of sand production. The results showed that pressure depletion reduces the critical drawdown pressure of sand production, and the reduction level is less than that of pore pressure; while the strength increase resulted from pressure depletion increases the critical drawdown pressure of sand production and reduces the probability of sand production. The establishment of the prediction model provides the guidance for actual production decisions in pressure depleted reservoirs.

Keywords*: pressure depleted reservoir, pore pressure, horizontal in-situ stress, rock strength, Mohr-Coulomb strength criterion, sand production*

Introduction. Sand production, which is the failure of formation due to in-situ stress and fluid flow, is widespread in the production of oil and gas sandstone reservoirs [1]. A great deal of work has been done in the general area of sand production. Some models view sand production as a mixed hydro mechanical process [2]. Some others base their sanding model solely on mechanical stability [3]. For brittle rock with high strength, sand production has only mechanical failure [4]. With the development of oil and gas, if the formation energy cannot be effectively supplied, the reservoir pressure will deplete, which will increase the risk of sand production [5]. Sand production of depleted reservoir has been researched [3, 5, 6], but the influence of pressure depletion on in-situ stress and the influence of pressure depletion on reservoir strength hadn't been considered. Mohr–Coulomb criterion is the mostly used failure criterions for sand prediction [7]. This paper analyzes the effect of pressure depletion on in-situ stress and reservoir strength, and critical bottom hole flowing pressure model in pressure depleted reservoir is established based on Mohr-Coulomb strength criterion.

Pressure depletion influence on in-situ stress. Owing to the fact that overburden pressure is produced by the gravity of the overburden formation, the pressure depletion of reservoirs shows little effects on the overburden pressure. Therefore, the deformation of the horizontal plane caused by pressure depletion in the oil and gas formations, which have flat and thick structure as well as the similar elastic property of the pores with the surrounding rock, is too small to be neglected. That is to say, the oil and gas formations are in the state approximating to the uniaxial compression without horizontal deformation, as shown in the following equation

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

Where $\Delta\varepsilon_H$ and $\Delta\varepsilon_h$ are the strains on the maximum and minimum horizontal stress directions caused by pressure depletion, respectively.

According to the generalized Hoek's law, the constitutive relation before the reservoirs developed is

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

Where E is the Young's modulus; μ is Poisson's ratio; σ_H and σ_h are the maximum and minimum horizontal in-situ stresses, respectively; σ_v is the overburden pressure; P_p is the original pore pressure; and α is the Biot's coefficient.

When the pore pressure in the reservoirs depletes to P_{p1} and the overburden pressure σ_v is regarded as constant, the horizontal constitutive relation meets the following formula

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

Based on the assumption of (1), we have

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

By substituting (2) and (3) into (4), calculate and rearrange

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

Where σ_{H1} and σ_{h1} are the maximum and minimum horizontal in-situ stresses after the pressure depletion.

Stresses around the borehole. The original in-situ stress exists in the rocks of formation in all oil and gas wells before drilling. Therefore, after the well being drilled, the fluid pressure replaces the support provided by the rock drilled away and the stress on the surrounding rock of boreholes is redistributed inevitably [1]. Suppose that the formation around the borehole is a porous elastic medium, the stress distribution can be solved using the following mechanical model: regarding a round hole, it bears uniformly internal pressure, two horizontal in-situ stresses in the infinity, and overburden pressure on vertical direction [3], as illustrated in fig. 1 [8]. As maximum stress is on the borehole wall, merely a stress distribution formula on the borehole wall is given in the research. After the reservoir pressure depletes to P_{P1}, the effective stress on the borehole wall of the vertical well is

$$\begin{cases} \sigma'_r = P_{wf} - \alpha P_{wf} \\ \sigma'_\theta = (1-2\cos 2\theta)\left[\sigma_H + \frac{1-2\mu}{1-\mu}\alpha(P_{p1} - P_P)\right] + \\ \quad +(1+2\cos 2\theta)\left[\sigma_h + \frac{1-2\mu}{1-\mu}\alpha(P_{p1} - P_P)\right] - . \\ \quad -P_{wf} - \alpha P_{wf} \\ \sigma'_z = \sigma_V - 2\mu(\sigma_H - \sigma_h)\cos 2\theta - \alpha P_{wf} \end{cases} \quad (6)$$

Where σ'_r, σ'_θ and σ'_z are effective stresses on the radial, tangential, and vertical directions of the borehole respectively; P_{wf} is the fluid column pressure in the well; θ is the borehole circumferential angle.

In oil and gas production, the formation fluid will flow into the borehole, and the additional stress induced by seepage on the borehole wall is as follows

$$\begin{cases} \sigma_{r1} = -f(P_{wf} - P_{P1}) \\ \sigma_{\theta 1} = \left[\frac{\alpha(1-2\mu)}{1-\mu} - f\right](P_{wf} - P_{P1}). \\ \sigma_{z1} = \left[\frac{\alpha(1-2\mu)}{1-\mu} - f\right](P_{wf} - P_{P1}) \end{cases} \quad (7)$$

Where σ_{r1}, $\sigma_{\theta 1}$ and σ_{z1} are the radial, circumferential, and vertical stresses caused by the transfusion of fluid respectively, f is the porosity of the reservoirs.

By superposing (6) and (7), the effective stress distributing on the borehole wall after the reservoir pressure depletes to P_{P1} is

$$\begin{cases} \sigma'_r = P_{wf} - \alpha P_{wf} - f(P_{wf} - P_{P1}) \\ \sigma'_\theta = (1-2\cos 2\theta)\left[\sigma_H + \frac{1-2\mu}{1-\mu}\alpha\left(P_{p1} - P_p\right)\right] + \\ \quad +(1+2\cos 2\theta)\left[\sigma_h + \frac{1-2\mu}{1-\mu}\alpha\left(P_{p1} - P_p\right)\right] - . \\ \quad -P_{wf} - \alpha P_p + \left[\frac{\alpha(1-2\mu)}{1-\mu} - f\right](P_{wf} - P_{P1}) \\ \sigma'_z = \sigma_V - 2\mu\left(\sigma_H - \sigma_h\right)\cos 2\theta - \alpha P_{wf} + \\ \quad + \left[\frac{\alpha(1-2\mu)}{1-\mu} - f\right](P_{wf} - P_{P1}) \end{cases} \quad (8)$$

Pressure depletion influence on the reservoir strength. The depletion of pore pressure in the reservoirs not only changes the original in-situ stress, but also influences the reservoir strength. In the process of pressure depletion, with a generally constant external stress, the overburden rocks stress namely, the framework stress of the rock increases. As a result, the reservoir is compacted and the porosity reduces. The porosity of the rocks reflects the dense degree of the rock, and the larger the porosity is, the lower is the compressive strength. Generally, the compressive strength of the rocks increases with the increase of the compactness. It indicates the concrete influence of porosity reduction on the compressive strength.

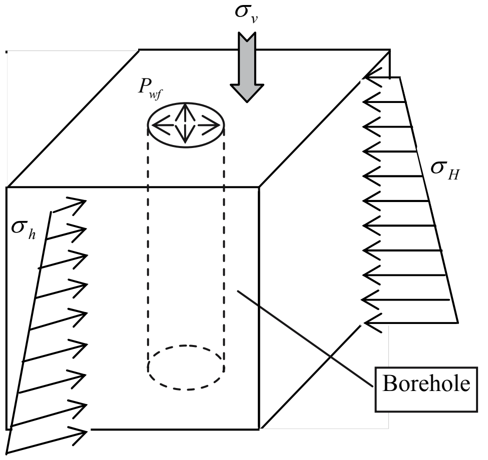

Fig. 1. Mechanical model of an open hole [8]

Based on the effective stress principle of porous media and the definition of porosity, Liu et al [9] derived the formula for calculating the variation of porosity with formation pressure under constant overburden pressure condition, according to the compressibility and the correlativity of rocks.

$$df = \left[C_S f\left(1-2f\right)+\left(C_b - C_S\right)\left(1-f\right)\right]dP. \quad (9)$$

Where C_S and C_b are the frame compressibility and compressibility of rocks, respectively.

The porosity of the reservoirs after pressure depletion is

$$f_1 = f_0 + \left[C_S f\left(1-2f\right)+\left(C_b - C_S\right)\left(1-f\right)\right]dP. \quad (10)$$

Where f_1 is the porosity after pressure depletion and f_0 is the original porosity.

Lots of research has been made on the relations between the porosity and the uniaxial strength. The relations between rock strength and porosity have been explored by employing numerical simulations and laboratory tests. In pressure depleted reservoirs, the variation of uniaxial compressive strength in the reservoirs after pressure depletion is [10]

$$UCS_1 = UCS_0 \frac{\exp\left(-10 f_1\right)}{\exp\left(-10 f_0\right)}. \quad (11)$$

Where UCS_1 is the uniaxial compressive strength (UCS) of the reservoir after pressure depletion; UCS_0 is the original strength of the reservoirs.

By combining (10) and (11), the change law of reservoir strength with pressure depletion is obtained. fig. 2, 3 demonstrate the change laws of reservoir porosity and the strength with pressure depletion, respectively. The porosity decreases apparently with the pressure depletion and the reservoir strength increases distinctly. The pore pressure changes by 20 MPa, and the strength increases by 14.6 MPa. The changes are significant in sand production.

Prediction model for critical bottom hole flowing pressure in pressure depleted reservoirs. The research employed an open-hole completion in the model, and the surrounding rocks of the borehole have high strength [3]. Therefore, sand production occurs only when the formation is damaged. The Mohr-Coulumb criterion that takes into account the fluid pressure in the pores of the rocks and expressed using the principle stress is

$$\sigma_1 = \sigma_3 \tan^2\left(45^0 + \frac{\phi}{2}\right) + 2C\tan\left(45^0 + \frac{\phi}{2}\right). \quad (12)$$

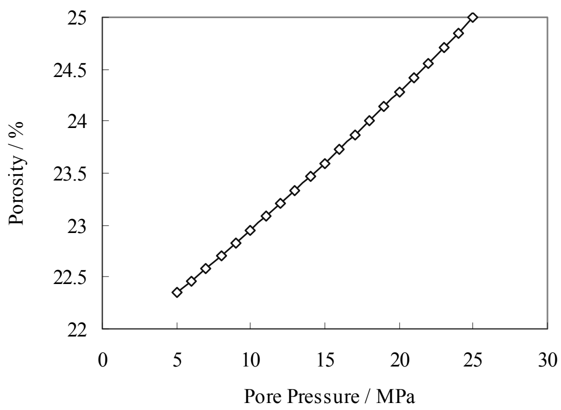

Fig. 2. Change law of reservoir porosity with pore pressure

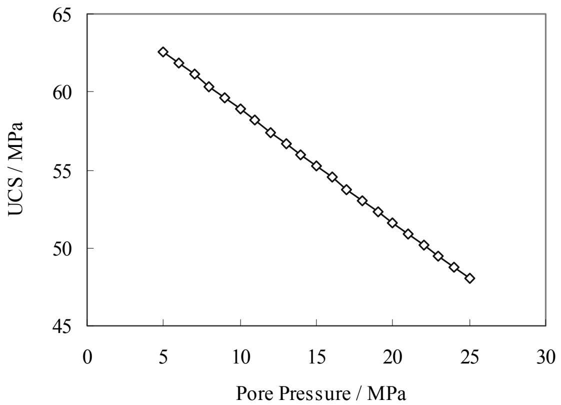

Fig. 3. Change law of reservoir strength with pore pressure

Where σ_1 and σ_3 are the maximum and minimum effective principle stresses; φ is the internal friction angle of the rocks; C is the cohesion of the rock.

Al-Awad [11] built the relation between the cohesion of the rocks and the UCS; the cohesion of pressure depleted reservoirs therefore is

$$C = -0.417 + 0.289UCS - 0.000519UCS^2. \quad (13)$$

Since the uniaxial tests meet the requirement that $\sigma_3 = 0$, by substituting (13) into (12), the relation between the internal friction angle and UCS is

$$\tan\left(45^0+\frac{\phi}{2}\right)=\frac{1}{2}\frac{UCS}{-0.417+0.289UCS-0.000519UCS^2}. \quad (14)$$

When the Mohr's circle constructed by the effective stress on the radial and circumferential direction exceeds the strength that can damage the rocks, shear failure for the rocks of sidewalls and sand production in oil wells were caused. After pressure depletion, owing to the formation stress state changes, sanding can occur for the formation which has never produced sand before if the drawdown pressure of sanding production does not change. In the process of pressure depletion, the critical bottom hole flowing pressure, at which there is no sand production, continuously changes with pore pressure. By substituting (8) into (12), when the reservoir pressure depletes from P_P to P_{P1}, the critical bottom hole flowing pressure is

$$P_{wf}=\frac{3\sigma_H-\sigma_h+(3\alpha\frac{1-2\mu}{1-\mu}-f)P_{P1}-2\alpha\frac{1-2\mu}{1-\mu}P_P-2C\tan\left(45^\circ+\frac{\phi}{2}\right)-f\tan^2\left(45^\circ+\frac{\phi}{2}\right)}{(1-f-\alpha)\tan^2\left(45^\circ+\frac{\phi}{2}\right)-\alpha\frac{1-2\mu}{1-\mu}+f+\alpha+1}. \quad (15)$$

Where P_{wf} is the critical bottom hole flowing pressure after pressure depletion, and the other symbols are the same with those in above sections.

When $P_{P1}=P_P$, (15) degrades to the prediction model for critical bottom hole flowing pressure at initial stage of the reservoir without pressure depletion.

Analysis. When the bottom hole flowing pressure is smaller than the critical bottom hole flowing pressure, sand production occurs in oil and gas wells. The critical drawdown pressure of sand production in pressure depleted reservoirs is

$$\Delta p=p_{p1}-p_{wf}. \quad (16)$$

When $P_{P1}=P_P$, (16) degrades to the prediction model for critical drawdown pressure of sanding production at the initial stage of the reservoir.

Fig. 4 illustrates the change law of critical drawdown pressure of sanding production with reservoir pressure with and without considering strength variation. It indicates that the critical drawdown pressure reduces with the decrease of reservoir pressure and the reducing speed of the critical drawdown pressure is always slower than that of the pore pressure. In other words, the bottom hole flowing pressure reduces gradually in oil and gas production. Therefore, it is inadvisable to keep a constant producing drawdown pressure, as well as a constant bottom hole flowing pressure, in the production of pressure depleted reservoirs. With a constant drawdown pressure, sanding possibly occurs on the later stage of the recovery and influences the following production. While a constant critical bottom hole flowing pressure results in a conservative drawdown pressure of sanding production, which limits the production ability of oil and gas wells to some extent. The critical drawdown pressure can be increased by taking into account the strength increase caused by pressure depletion; while the critical drawdown pressure is small and limits the recovery ability of oil and gas wells without considering the strength change.

Conclusions.

1. According to the basic mechanical principles, the change law of in-situ stress with reservoir pressure in pressure depleted reservoirs was explored. Additionally, the dynamic distribution formula of the stress on the surrounding rocks of the borehole in the production of pressure depleted reservoirs was obtained.

2. The relation between reservoir pressure change and strength formation was acquired. The depletion of reservoir pressure caused the reduction of porosity and the increase of formation strength.

3. Based on the influence of pressure depletion on reservoir strength, the calculation model for critical bottom hole flowing pressure in pressure depleted reservoirs was constructed.

4. The pressure depletion reduced the critical drawdown pressure of sand production, but the decrease level was less than that of the pore pressure. The critical drawdown pressure of sanding tended to increase to therefore decrease the sanding probability due to the increase of strength caused by pressure depletion.

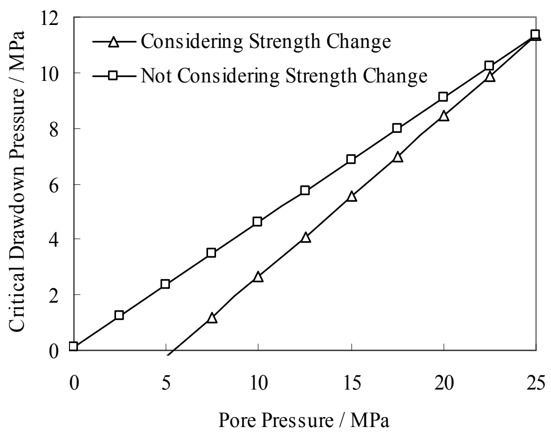

Fig. 4. The variation of critical drawdown pressure of sand production with reservoir pressure

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За довгий час експлуатації, більшість родовищ уже вступили до пізньої стадії розробки, і поровий тиск серйозно зменшився. Зниження тиску не лише впливає на територію родовища, й при цьому змінює напружений стан довкола свердловин, але й позначається на міцності порід, викликаючи ущільнення та зниження пористості пласта. Ці два чинники, підсилюючи один одного, здійснюють вплив на критичні просідання тиску піщанистих порід. На підставі узагальненого закону Хука, теоретична формула представляє зміни двох горизонтальних напруг порового тиску. Використовуючи формулу розподілу напруги довкола свердловини, було проаналізовано зменшення тиску у виснажених пластах родовищ, що вступили до пізньої стадії розробки. Крім того, при вивченні взаємозв'язку зниження пластового тиску зі зміною межі міцності породи була побудована модель для розрахунку критичного тиску у виснажених пластах родовищ. Було також проаналізовано, за допомогою моделі, вплив зниження тиску на критичну просадку та винесення піску. Результати показали, що зниження тиску впливає на критичну просадку піщанистих порід менше, ніж на рівень зниження порового тиску; у той же час збільшення міцності в результаті зниження тиску збільшує критичну просадку шліфування піщанистих порід і знижує вірогідність винесення піску. Створена модель прогнозування дає можливість приймати ефективні виробничі рішення на виснажених родовищах, що вступили до пізньої стадії розробки, поровий тиск яких серйозно зменшився.

Ключові слова: *виснажене родовище, тиск у порах, горизонтальний тиск усередині пласта, міцність породи, критерій міцності Мора-Кулона, винесення піску*

За длительное время эксплуатации большинство месторождений уже вступили в позднюю стадию разработки, и поровое давление серьезно уменьшилось. Снижение давления не только влияет на территорию месторождения, при этом изменяет напряженное состояние вокруг скважин, но и сказывается на прочности пород, вызывая уплотнение и снижение пористости пласта. Эти два фактора, усиливая друг друга, оказывают влияние на критические просадки давления песчанистых пород. На основании обобщенного закона Хука, теоретическая формула представляет изменения двух горизонтальных напряжений порового давления. Используя формулу распределения напряжений вокруг скважины, было проанализировано уменьшение давления в истощенных пластах месторождений, которые вступили в позднюю стадию разработки. Кроме того, при изучении взаимосвязи снижения пластового давления с изменением предела прочности породы была построена модель для расчета критического давления в истощенных пластах месторождений. Было также проанализировано, при помощи модели, влияние снижения давления на критическую просадку и вынос песка. Результаты показали, что снижение давления влияет на критическую просадку песчанистых пород меньше, чем на уровень снижения порового давления; в то же время увеличение прочности в результате снижения давления увеличивает критическую просадку шлифования песчанистых пород и снижает вероятность выноса песка. Созданная модель прогнозирования дает возможность принимать эффективные производственные решения на истощенных месторождениях, вступивших в позднюю стадию разработки, поровое давление которых серьезно уменьшилось.

Ключевые слова: *истощенное месторождение, давление в порах, горизонтальное давление внутри пласта, прочность породы, критерий прочности Мора-Кулона, вынос песка*

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