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裸眼井出砂预测模型的解析分析

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摘要　根据弹性力学的有关知识, 分析了考虑油层流体渗流作用时, 裸眼井周围的应力分布情况。根据Mohr—Coulomb准则, 建立了相应的出砂预测模型, 给出油井出砂时临界井底流压的计算方法。分析了储层压力、岩石抗压强度及原地应力状态对出砂的影响。研究结果表明, 储层压力、地应力增大, 岩石抗压强度变小时, 临界井底流压升高, 井壁更易出砂。

关键词　裸眼完井　出砂　预测　地应力

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在石油开采过程中, 由水动力冲刷等作用引起的疏松砂岩储层出砂是导致储层损害和产能降低的主要原因。出砂不仅会导致油井减产或停产及地面和井下设备的腐蚀, 而且会使套管损坏、油井报废。

疏松砂岩油藏出砂机理十分复杂, 影响因素很多, 包括地质力学因素、岩石力学性质、储层的综合性质、工程因素等。这些因素相互影响、相互作用, 使出砂问题的理论研究变得十分复杂。采用裸眼完井的油井, 其地层一般具有较高的强度, 只有在地层发生破坏时, 才会引起出砂。对于这类储层, 防砂的关键在于防止地层破坏。

通过解析分析的方法, 对裸眼井围岩的应力状态进行了分析, 给出油层出砂时临界井底流压的计算方法, 并讨论了储层压力、地应力、岩石强度对油层出砂的影响。

1　井壁围岩应力状态分析

井壁附近的岩石处于地层深处, 既受地应力作用, 又受到钻采扰动力等的作用, 所以井壁周围岩体大多处于损伤软化状态, 易于发生剪切破坏而出砂。因此对井壁的应力状态进行分析对于预测油井出砂具有重要意义。油井井壁由于受流体渗透力作用, 井壁围岩应力要重新分布。假设井壁围岩是化学稳定的, 即岩石充水后没有膨胀和收缩, 不改变岩石原来的物理力学性质, 并假设岩石内的渗流满足达西定律, 那么只要确定出岩石内各部分渗透孔隙压力的变化规律, 即可求得井壁围岩的应力状态。

为了进行解析分析, 可将井壁简化为厚壁筒问题(如图1所示)。厚壁圆筒由多孔材料组成, 圆筒中受到流体渗透力的作用, 形成一个孔隙流体压力场, 每点产生渗透力。设井眼半径为 a, 井壁外缘半径为 b, 井底流压为 p_a, 远场流压为 p_0。

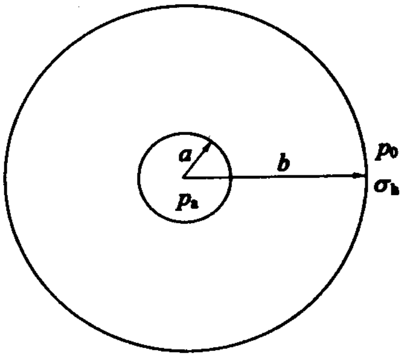

图1　井壁力学模型

考虑渗透情况下井壁围岩的平衡微分方程为

$$\frac{\mathrm{d}\sigma_r}{\mathrm{d}r}+\frac{\sigma_r-\sigma_\theta}{r}-\eta_m\frac{\mathrm{d}p_w}{\mathrm{d}r}=0 \tag{1}$$

式中, p_w 为孔隙压力, 随 r 而变化; η_m 为与岩土材料相关的常数。

经考察, 如果用应力函数 F 来确定, 并写成如下形式, 即可满足式(1)

$$\left.\begin{aligned}\sigma_r&=\frac{F}{r}\\ \sigma_\theta&=\frac{\mathrm{d}F}{\mathrm{d}r}-\eta_m r\frac{\mathrm{d}p_w}{\mathrm{d}r}\end{aligned}\right\} \tag{2}$$

用径向应变和切向应变表示的变形协调方程为

$$\varepsilon_\theta-\varepsilon_r+r\frac{\mathrm{d}\varepsilon_\theta}{\mathrm{d}r}=0 \tag{3}$$

井壁围岩的本构方程为

$$\begin{cases} \varepsilon_x = \dfrac{1}{E}[\sigma_x - \mu(\sigma_y + \sigma_z)] \\ \varepsilon_y = \dfrac{1}{E}[\sigma_y - \mu(\sigma_x + \sigma_z)] \\ \varepsilon_z = \dfrac{1}{E}[\sigma_z - \mu(\sigma_y + \sigma_x)] \end{cases} \tag{4}$$

将式(2)的应力代入本构方程(4)，再把这样得到的应变代入式(3)，就可得到以应力函数 F 表示的变形协调方程

$$r\frac{d^2F}{dr^2} + \frac{dF}{dr} - \frac{F}{r} = \frac{\eta_m}{1-\mu} \cdot r\frac{dp_w}{dr} + \eta_m r \nabla^2 p_w \tag{5}$$

方程式(5)是控制方程式。只要知道了 p_w 的分布规律，即可解这个微分方程求 F，从而把 F 代入式(3)确定在渗透力作用下的应力 σ_r、σ_θ。假定井壁渗流服从达西定律，满足 $\nabla^2 p_w = 0$，则井壁孔隙压力按下列规律分布

$$p_w = p_a + (p_0 - p_a)\frac{\ln\dfrac{r}{a}}{\ln\dfrac{b}{a}} \tag{6}$$

对上式求导得

$$\frac{dp_w}{dr} = \frac{p_0 - p_a}{\ln\dfrac{b}{a}} \cdot \frac{a}{r} \cdot \frac{1}{a} = \frac{p_0 - p_a}{\ln\dfrac{b}{a}} \cdot \frac{1}{r} \tag{7}$$

将式(7)代入式(5)得

$$r\frac{d^2F}{dr^2} + \frac{dF}{dr} - \frac{F}{r} = \frac{\eta_m}{1-\mu} \cdot \frac{p_0 - p_a}{\ln\dfrac{b}{a}} \tag{8}$$

上式的通解为

$$F = C_1 r + C_2\frac{1}{r} + \frac{\eta_m(p_0 - p_a)}{2(1-\mu)\ln\dfrac{b}{a}} \cdot r\ln r \tag{9}$$

因此，井壁的径向应力可表示为

$$\sigma_r = \frac{F}{r} = C_1 + C_2\frac{1}{r^2} + \frac{\eta_m(p_0 - p_a)}{2(1-\mu)\ln\dfrac{b}{a}}\ln r \tag{10}$$

$$\sigma_\theta = \frac{dF}{dr} - \eta_m r\frac{dp_w}{dr} \tag{11}$$

式中，C_1、C_2 为待定常数，必须由边界条件确定。由边界条件

$$\begin{cases} \sigma_r|_{r=a} = p_a(1-\eta_m) \\ \sigma_r|_{r=b} = \sigma_h \end{cases}$$

得井壁的应力为

$$\sigma_r = \frac{b^2(a^2 - r^2)}{r^2(b^2 - a^2)}\left[p_a(1-\eta_m) - \sigma_h + \frac{\eta_m(p_0 - p_a)}{2(1-\mu)}\right] + p_a(1-\eta_m) + \frac{\eta_m(p_0 - p_a)\ln\dfrac{r}{a}}{2(1-\mu)\ln\dfrac{b}{a}} \tag{12}$$

$$\sigma_\theta = p_a(1-\eta_m) - \frac{b^2(r^2 + a^2)}{r^2(b^2 - a^2)}\left[p_a(1-\eta_m) - \sigma_h + \frac{\eta_m(p_0 - p_a)}{2(1-\mu)}\right] - \frac{\eta_m(p_0 - p_a)\ln\dfrac{r}{a}}{2(1-\mu)\ln\dfrac{b}{a}} - \frac{\eta_m(p_0 - p_a)}{\ln\dfrac{b}{a}} \tag{13}$$

假定 $a = 0.25$m，$b = 20$m，$\sigma_h = 28$MPa，$p_0 = 10$MPa，$p_a = 1$MPa，$\eta_m = 2/3$，$\mu = 0.3$，则根据式(12)，(13)可计算出井壁应力分布曲线，见图 2～图 3。与不考虑渗透作用情况(即孔隙压力为零)的应力分布曲线作对比发现，考虑渗水情况和不考虑渗水情况应力计算结果相差很大，径向应力和切向应力均比不考虑渗透情况时小。

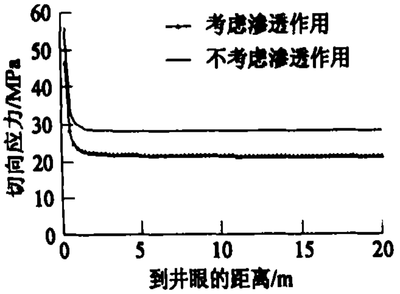

图 2　井壁切向应力分布

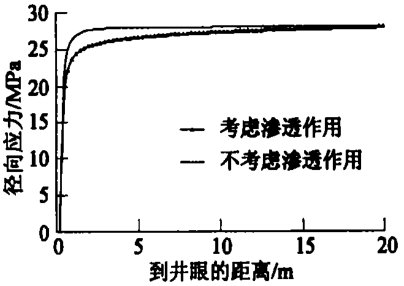

图 3　井壁径向应力分布

2　出砂预测模型的建立

采用裸眼完井的油井，井壁围岩一般具有较高的强度，只有在地层发生破坏后，才可能引起出砂。通常井壁围岩的破坏方式为剪切破坏，根据 Mohr—Coulomb 准则可知，此时径向和切向应力满足

$$\sigma_\theta - \sigma_r N_\varphi = \eta_m p(1 - N_\varphi) + \sigma_c \tag{14}$$

其中，$N_\varphi = (1 + \sin\varphi)/(1 - \sin\varphi)$，$\varphi$ 为岩石的内摩

擦角；σ_c 为岩石的抗压强度。

由于剪切破坏一开始发生在井壁，因此井壁刚开始破坏时满足 Mohr－Coulomb 准则，将井壁的径向应力和切向应力代入式(10)并化简得

$$\sigma_c = p_a(1-2\eta_m) - \frac{2a^2b^2}{a^2(b^2-a^2)}\left[p_a(1-\eta_m)-\sigma_h+\frac{\eta_m(p_0-p_a)}{2(1-\mu)}\right] - \frac{\eta_m(p_0-p_a)}{2(1-\mu)\ln\frac{b}{a}} - \frac{\eta_m(p_0-p_a)}{\ln\frac{b}{a}} - N\varphi p_a(1-2\eta_m) \quad (15)$$

在上式中，可控制的变量只有 p_a，由上式可求得发生剪切破坏时井底流压为

$$p_a = \frac{\sigma_c + \frac{\eta_m p_0}{\ln\frac{b}{a}} - \frac{2b^2a^2}{a^2(b^2-a^2)}\sigma_h - \frac{b^2a^2}{a^2(b^2-a^2)}\frac{\eta_m p_0}{(1-\mu)}}{N\varphi - 1 - \frac{2b^2a^2(\eta_m-1)}{a^2(b^2-a^2)} - \frac{b^2a^2\eta_m}{a^2(b^2-a^2)(1-\mu)} + \frac{\eta_m}{\ln\frac{b}{a}}} \quad (16)$$

假设 $b=\infty$，则上式变为

$$p_a = \frac{-\sigma_c + 2\sigma_h + \frac{\eta_m p_0}{1-\mu}}{1+N\varphi-2\eta_m-\frac{\eta_m}{1-\mu}} \quad (17)$$

从上式可知，油井出砂时的临界井底流压与岩石强度 σ_c、地应力 σ_h 和油藏压力 p_0 呈线性关系。岩石强度越大，出砂时的临界井底流压越大；地应力和油藏压力越大，临界井底流压越小。如果假定 $\varphi=30°$，$\sigma_h=28\text{MPa}$，$p_0=15\text{MPa}$，$\sigma_c=65\text{MPa}$，$\eta_m=2/3$，$\mu=0.3$，则可计算出临界井底流压为：$p_a=3.08$ MPa。

3　储层参数对油井出砂的影响

假定式(17)中，$\varphi=30°$，$\sigma_h=28\text{MPa}$，$\sigma_c=60\text{MPa}$，$\eta_m=2/3$，$\mu=0.3$，则井底流压与油藏压力之间的关系为

$$p_a = -2.3333 + 0.55555p_0 \quad (18)$$

图4为临界井底流压与储层压力之间的关系曲线。从图4可看出，储层压力越高，临界井底流压越高，油井越容易出砂。

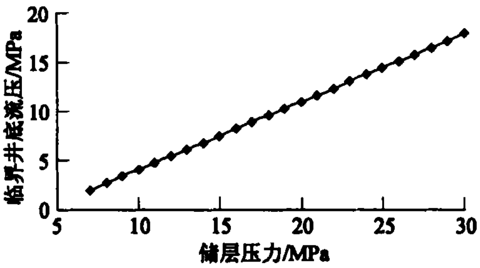

图4　储层压力与临界井底流压的关系

假定式(17)中，$\varphi=30°$，$\sigma_h=28\text{MPa}$，$p_0=15\text{MPa}$，$\sigma_c=65\text{MPa}$，$\eta_m=2/3$，$\mu=0.3$，则井底流压与岩石抗压强度之间的关系为

$$p_a = -0.58333\sigma_c + 41 \quad (19)$$

图5比较直观地反映了临界井底流压与岩石抗压强度之间的关系。从图5可看出，随着岩石强度的增加，临界井底流压减小。当岩石的强度很小时，临界井底流压较高，此时油井易于出砂。岩石的抗压强度越大，油井越不容易出砂。

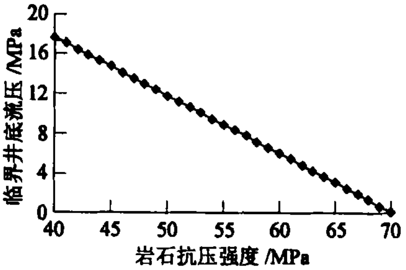

图5　临界井底流压与岩石抗压强度的关系

假定地应力为变量，其它参数为常量，如令 $\varphi=30°$，$p_0=15\text{MPa}$，$\sigma_c=65\text{MPa}$，$\eta_m=2/3$，$\mu=0.3$，则根据式(17)可得

$$p_a = -29.5835 + 1.166657\sigma_h \quad (20)$$

图6为临界井底流压与地应力的关系，可以看出，地应力越大，临界井底压力越高，越容易出砂。

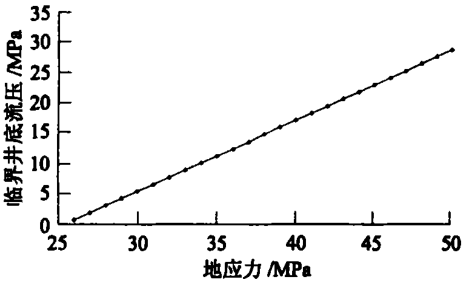

图6　临界井底流压与地应力的关系

4　结论

(1)通过解析分析，得出考虑流体渗透作用情况

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2.5mm 之间的有 7 井次,处理半径大于 2.5m 的 7 井次。处理半径对防砂堵水效果的影响见表 3。

表 **3**　处理半径对防砂堵水效果的影响

处理半径/m	措施前			措施后			有效期/d
	日产液/t°d^{-1}	日产油/t°d^{-1}	含水/%	日产液/t°d^{-1}	日产油/t°d^{-1}	含水/%	
＜1.5	86.9	1.3	98.5	77.7	2.4	97.0	107
1.5~2.5	95.9	1.8	98.2	87.4	3.3	96.3	113
＞2.5	80.2	2.2	97.3	60.1	4.1	93.2	195

从表 3 可看出,处理半径越大,防砂和堵水效果越好。

3.4　施工压力升幅

施工压力升幅小于2MPa 的有5 井次,施工压力在2~4MPa 的 7 井次,施工压力升幅在 4MPa 以上的8 井次。施工压力升幅对防砂堵水效果的影响见表4。

表 **4**　施工压力升幅对防砂堵水效果的影响

压力升幅/MPa	措施前			措施后			有效期/d
	日产液/t°d^{-1}	日产油/t°d^{-1}	含水/%	日产液/t°d^{-1}	日产油/t°d^{-1}	含水/%	
＜2	92.3	1.3	98.6	84.5	2.3	97.3	101
2~4	81.9	2.1	97.4	70.4	3.6	94.9	183
＞4	86.1	1.9	97.9	77.9	5.1	93.5	149

从表 4 可看出,施工压力升幅越高,防砂堵水效果越好。而施工压力的变化与挤入剂量有关,一般剂量越大(封堵半径也越大),压力上升的幅度相应越大,效果也越好。

通过以上分析,可以得出:层数、处理半径和施工时的压力变化 3 个因素直接影响着胶合砂的防砂堵水效果。

4　结论

(1)JHS—3 胶合砂是由无机硅酸粒熟料复合而成的一种防砂堵水剂,所形成挡砂体的抗压强度为 4.5~6.0MPa,抗折强度为 2.0~3.0 MPa,具有良好的渗透性。

(2)胶合砂能有效地改变产液剖面,具有防砂和堵水的双重效果,特别是针对粒径小于 0.15mm 的粉细砂甚至粘土砂,具有独到的防砂效果,有效期在150d 以上,增油降水效果明显。

(3)在单井层数和油层厚度固定的情况下,增加挤入的剂量,能加大封堵半径,使压力上升幅度增大,提高了防砂和堵水的效果。另外,也应根据地层渗透率的差异和吸液能力的不同,选择合理的注入压力和排量,以提高防砂效果和堵水的选择性。

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时,井壁围岩应力分布的解析表达式。从结果可看出,考虑流体渗透作用时的径向和切向应力均比不考虑渗透作用时小。

(2)利用 Mohr—Coulomb 准则,建立了裸眼完井井壁出砂的数学模型。推导出油井出砂时,临界井底流压的计算公式。

(3)研究发现,储层压力增加、地应力增大、岩石抗压强度变小时,临界井底流压升高,井壁更易于出砂。

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effect. The exact solutions obtained for a well producing at a constant rate from a radial drainage area confined outer boundary condition are expressed in terms of ordinary Bessel functions. The numerical computation of these solutions is made by Crump numerical inversion method and the behavior of the systems is studied as a function of various reservoir parameters. The new model is numerically stable. The typical curve in confined formation condition is drawn up by numerical inversion method.

Key words well-testing mathematical model crossflow effective hole diameter inversion of Laplace Transform layered Reservoir

PREDICTION TO SAND PRODUCTION IN FORMATION BY ARTIFICAL NEURAL NETWORK TECHNOLOGY

by Fan Xingwo(Petroleum Engineering Tech. Research Inst. of Changqing Petroleum Exploration Bureau), Li Xiangfang, Tong Min, Hu Chaizhi, Zhao Ping

Abstract A new method to predict sand production in oil and gas by the Artificial Neural Network (ANN) is described in the paper. Viscous oil reservoirs are characterized by poor consolidation, poor diagenesis. Especially, the oil is highly viscous in Du32 of Liaohe Oilfield and Cheng Bei of Shengli Oilfield. There exists great deviation resulted from the sand production predicted by traditional methods in the test. Moreover, lack of the whole core samples in the two blocks, the method of core flow experiment to predict sand production is much too inaccurate. In order to settle the problem, the method of sand production predicted by ANN is applied in the two oilfields. According to the field data of the formation, fluid, log analysis and performance in oil and gas wells, based on the analysis of sand production factors, BP Artificial Neural Network is used to predict sand production by studying samples. The application in this two fields shows the good results can be produced by the method of ANN.

Key words sand production prediction BP Artificial Neural Network Liaohe Oilfield Shengli Oilfield

ANALYTICAL ANALYSIS OF SAND PRODUCTION MODEL OF OPEN-HOLE COMPLETION WELL

by Zeng Liufang, Liu Jianjun(Beijing Campus of China University of Mining and Technology)

Abstract Based on elastic-plastic mechanics and damaged Mechanic, considering the effect of fluid flow in strata, the stress distribution around open-hole completion well-bore is analyzed. Using Mohr-Coulomb criteria, the sand production model is founded. The calculating method of the critical fluid pressure of bottom hole is given. Influence of reservoir pressure, compressive strength of rock, production pressure difference, rock strength factor on sand production are also analysed, and the result shows that critical bottomhole pressure and wallbore production sand will take varies according to these parameters change.

Key words open hole completion sand production prediction strata stress

INTEGRATED MODEL FOR SAND CONTROL WELL PRODUCTIVITY EVALUATION AND PREDICTION

by Dong Changyin, Li Zhifen, Zhang Qi (University of Petroleum), Li Changyin

Abstract Normalized Productivity Index(NPI) and Productivity Ratio(PR) are firstly put forward to evaluate the effect of sand control measure on well productivity. According to the additional flow resistance areas formed by sand control measures and corresponding skin factors, considering the non-Darcy flow, the calculation method of NPI and PR is educed. If Inflow Performance Relationship(IPR) before sand controlling is at present, the IPR curve after sand controlling could be obtained by NPI. The application results indicate that this simplified model needs only fewer data but its results are very reliable. As an integrated sand control well productivity evaluation and prediction model, it can be used for most of present sand control method.

Key words sand control gravel pack productivity evaluation skin factor IPR

STUDY ON ORGANOSILICON HIGH TEMPERATURE SAND CONSOLIDATING TECHNIQUE AND APPLICATION OF VISCOUS CRUDE EXPLOITATION

by Wang Zhuofei(Petroleum University), Wu Jun, Wei Xinchun, Guo Shiyang, Huang Weihong

Abstract klamayi 6-9 viscous crude block are sandstone reservoir, formation structure is unconsolidated, the thermal recovery by injecting high temperature and high pressure steam will damage oil reservoir more heavier, make sand producing of producing well more seriously, which influence normal producing of this viscous crude reservoir block. Since 1991 wire wrapped sand control of mechanical sand control and hydroxy-aluminium sand control of chemical sand consolidating measures have been taken, but because sand control scope is limit, effect is bad, consolidating cycle is short, cost is high and so on, these measures can't be used widely. Without above disadvantages organosilicon modified sand consolidating technique has good high temperature sand consolidating property, tests indoors show under 300℃, compression strength of optimized organosilicon high temperature sand consolidating agent is above 4MPa, at the same time this agent take less damage to the formation, water phase permeability is above 0.60. the high temperature sand consolidating agent has been tested in 10 wells in field of 6—9 block viscous crude reservoir, efficiency is 98%, crude oil production is increased by 1180.7tons. After treatment, sand content of crude oil is very little. This technique has get satisfied effect, be worthwhile being popularized.

Key words sand consolidating sandstone reservoir steam flooding organosilicon high temperature sand consolidating agent

RESEARCH OF LH NET RESIN COVERED SAND USED IN MULTI-LAYERS SAND CONTROL

by Yan Jin'gen(GuDong Technology Research Institute of ShengLi Oilfield Limited Co.), Wang Zhijian, Zhang Guorong, Wang Wenkai, Li Hong, Qu Junbo

Abstract In the mid-later period of sand rock reservoir developing, the opened reservoir become more and more, loss caused by sand production become more and more serious. According to this problem, we developed LH net resin covered sand for multi-layers sand control.