PREDICTION OF CRITICAL FLOW RATE FOR PREVENTING SAND PRODUCTION USING THE MOGI-COULOMB FAILURE CRITERION

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ABSTRACT: *The production of sand particle has become serious problem to oil and gas well and was subject for study during the past years. Basically, sand production must be the results of a change in strength of the formation rock due to drilling, perforation and production operation and drag forces of the produced fluids. Sanding problems are often observed in fields after a period of relatively smooth operation. These occurrences usually coincide with an increase in depletion, water cut, or changes in the artificial lift mechanism used to produce the hydrocarbon. Sanding is detrimental to optimum field development and therefore, information about the possible advent and extent of sanding will be helpful in planning for completions and facilities. This paper presents an analytical study of the effects of oil flow rate on sand production to minimize sand production as well as optimize production and the result indicated that in unconsolidated sandstone layers, flow rate plays a key role in instability of these layers.*

Key words: *Sand production, Mogi-Coulomb, Drag force, Critical f low rate*

1. INTRODUCTION:

Sand production is a major problem in many oil and gas reservoirs worldwide. It can drastically reduce production rates, damage downhole/subsea equipment and surface facilities, thus increasing the risk of well failure. The problems are often observed in fields after a period of relatively smooth operation. These occurrences usually coincide with an increase in depletion, water cut, or changes in the artificial lift mechanism used to produce the hydrocarbon [1].

The potential of sand production is dependent on various factors including in-situ stresses, pore pressure, formation properties, depletion, water-cut, etc. If the strength of reservoir rock is low, it will require sand control. On the other hand, high strength rock is not expected to sand and therefore, does not require sand control. Reservoirs with rock strength from moderate to intermediate will benefit most from a sanding prediction study. The completion and operational decisions to prevent or control sanding need to be taken on a well to well basis by considering the individual characteristics of each well. The well characteristics include inclination and orientation in the in-situ stress field and formation strength.

Bianco [2] suggested that the sand/solids production phenomenon in oil producing wells would be associated to three basic sets of factors: magnitude of the in-situ stresses and its variations, pressure gradients, fluid flow velocity and changes in fluid saturation; strength factor (strength of the material, inter-particle friction; arcs of sand, capillary forces); operational factors (strategies of drilling and completion, production procedures and depletion of the reservoir). A description of operational aspects and other mechanisms related to sand/solids production are described in detail in [3]. Some researchers have studied techniques to control the sand/ solids production problem.

Additionally, other studies have presented analytical, numerical or laboratory procedures in order to understand and attempts to quantify sand/solids production rates. This paper presents an analytical study of the effects of oil flow rate on sand production to minimize sand production as well as optimize production in one of Iranian oil fields.

2. Sanding Prediction Methodology

If the failure of the intact rock can be predicted and prevented then the issue of produced sand transportation is of no concern. Therefore, a common starting point for most sanding prediction involved stress analysis and failure prediction around the perforation or openhole (i.e. geomechanical analysis). The sanding prediction model can also be used to assess the changes due to the critical drawdown pressure for an open hole or perforation that may occur over the life of a field undergoing depletion. This capability was used to assess the likely effects of depletion on the stability of the completions and on its susceptibility to sanding [1].

The process includes assessing the state of stress at the borehole wall or perforation tunnel, taking into account orientation and size of hole, and rock failure is then computed based on the mechanical properties of the rock and pore pressure. Stresses acting on the rock and around the borehole wall or perforation tunnel are also updated to account for depletion effects. The output is a continuous, depth-indexed profile of the critical drawdown pressure that will fail the reservoir rock, with results displayed for specific completion and specific depletion scenario. The analyses and results allow comparison of sanding risk for different completion strategies and at different stages in the life of the field. In addition, they can also identify high-risk zones in the completion interval that should be considered for isolation, as they may be particularly susceptible to sanding or may be expected to fail further under different production conditions e.g. later in field life.

3. In-situ stresses

In general the in-situ field stresses are the vertical principle stress and two unequal horizontal stresses.

In relaxed geological environments, these two horizontal stresses are less then vertical stress. In very active tectonic regimes, however, horizontal stress magnitude is higher than that of the vertical stress. Depending on the order of magnitude of these three principal stresses, different faulting regimes are defined [4]. To determine the magnitude of the vertical stress, it is usually assumed that it is solely due to the weight of the overburden.

That is:

$$\sigma_v = g\int_0^z \rho(z)\ dz \approx \bar{\rho} g z \qquad (1)$$

Where $\bar{\rho}$ is the average mass density of the overlying rock, g is the acceleration coefficient due to gravity, and h is the depth. If the density varies with depth, the vertical stress is determined by integrating the densities of the overlaying rocks. At the depths of interest, the vertical stress has a gradient in the range of (0.8–1.0 psi/ft)[3]. Hubbert and Willis (1957) presented a comprehensive discussion on the failure induced by hydraulic fracture where fractures expand perpendicular to the direction of minimum horizontal stress. In fact, determination of horizontal stress is significantly important since opening a crack to a certain extension is proportional to the tension created perpendicular to the crack screen in front of disruption. In isotropic and tectonically relaxed areas, minimum and maximum horizontal stresses are the same. These stresses are not equal where major faults or active tectonics exist.

In this study, the poroelastic horizontal strain model was used to determine the magnitudes of the minimum and maximum horizontal stresses [3]. Formulation of this model is expressed as:

$$\sigma_h = \frac{\nu}{1-\nu}(\sigma_v - \alpha P_p) + \alpha P_p + \frac{\nu E_s}{1-\nu^2}\varepsilon_1 + \frac{E_s}{1-\nu^2}\varepsilon_2 \qquad (2)$$

$$\sigma_H = \frac{\nu}{1-\nu}(\sigma_v - \alpha P_p) + \alpha P_p + \frac{\nu E_s}{1-\nu^2}\varepsilon_2 + \frac{E_s}{1-\nu^2}\varepsilon_1 \qquad (3)$$

In these equations ε_1 and ε_2 are tectonic strains in the field, P_p is the pore pressure , ν is the Poisson's ratio , α is the biot factor E_s is the static Yong modulus. Field scale measurements such as hydraulic fracturing, leak-off test (LOT), micro-fracture test and mini-fracture test can be performed to obtain an estimation of the magnitude of the minimum horizontal stress [6].

Figure 1 shows the stress and pressure profile in the study area. Based on drilling information pore pressure gradient is estimated 0.365 psi/ft.

4. Stresses at the borehole wall in a linear poroelastic formation

The maximum values of induced stresses occur in the direction of minimum horizontal stress. If the borehole wall is permeable, the pore pressure at the borehole wall is equal to the well pressure. This means that we must use wellbore flowing pressure rather than pore pressure when computing the effective stresses [7]. The maximum values of induced stresses at the wellbore wall are thus:

$$\sigma'_r = (1-\alpha)P_{wf} \qquad (4)$$

$$\sigma'_\theta = 3\sigma_H - \sigma_h - P_{wf} + B_e(P_{wf} - P_p) - \alpha P_{wf} \qquad (5)$$

$$\sigma'_z = \sigma_v + 2\nu(\sigma_H - \sigma_h) + B_e(P_{wf} - P_p) - \alpha P_{wf} \qquad (6$$

)

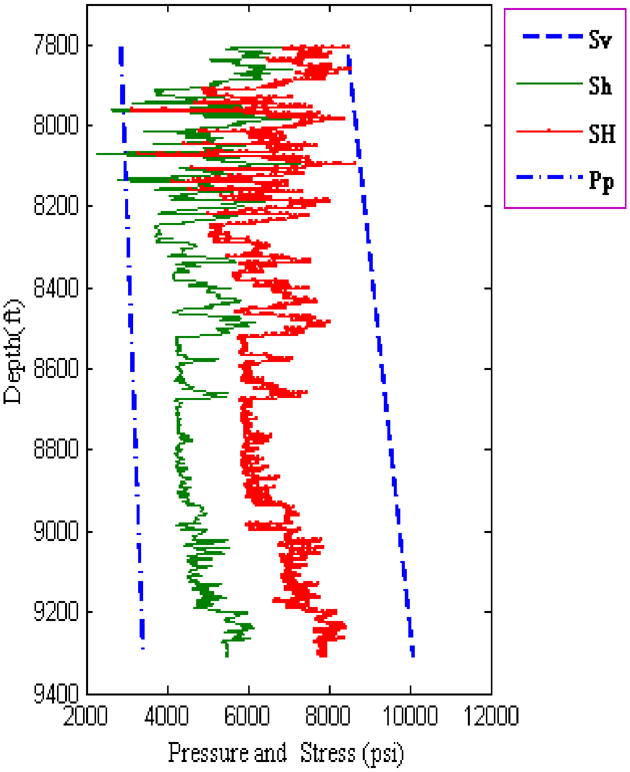

Figure 1: Pore pressure and In-situ stresses profiles.

5. Mogi–Coulomb failure criterion

The linear form of Mogi's criterion was presented by Al-Ajmi and Zimmerman (2005), that is

$$\tau_{oct} = a + b\sigma'_{m,2} \qquad (7$$

)

Where $\sigma'_{m,2}$ is the effective normal stress defined by

$$\sigma'_{m,2} = \frac{\sigma'_1 + \sigma'_3}{2} \qquad (8)$$

and τ_{oct} is the octahedral shear stress given by

$$\tau_{oct} = \frac{1}{3}\sqrt{(\sigma'_1 - \sigma'_2)^2 + (\sigma'_2 - \sigma'_3)^2 + (\sigma'_3 - \sigma'_1)^2} \qquad (9)$$

Where 'a' and 'b' are material constants which are simply related to cohesive strength (S_o) and internal friction angle (ϕ_f) as follows:

$$a = \frac{2\sqrt{2}}{3} S_o cos\phi_f \tag{10}$$

$$b = \frac{2\sqrt{2}}{3} sin\phi_f \tag{11}$$

As Mohr–Coulomb and Mogi–Coulomb criteria are exact when neglecting the intermediate principal stress, the influence of the cohesive strength on both failure criterion is the same. Therefore, the use of Mogi–Coulomb criterion introduces the additional impact of the intermediate principal stress on shear rock failure which is not considered in the conventional analysis. The developed models are applicable for an open hole vertical well. This model was first established by Al-Ajmi (2005) to evaluate the collapse pressure while drilling. However, in this study, the model was modified so that it can estimate sanding critical pressure during production. The modified model was mainly used to evaluate the optimum well path. In addition, an analytical solution was derived to obtain the optimal well path. In general, the models in this paper were developed with the following assumptions: (1) mechanical factors are governing the onset of damaging (other factors are ignored in this study), (2) brittle shear failure induced the sanding, (3) the horizontal stresses are anisotropic, and (4) The rock is homogenous with isotropic properties [7].

Based on triaxial compression tests the geomechanical properties of the target sandstone layer are shown in Table 1.

Table 1: Geomechanical parameters used in this study.

Cohesive Strength (psi)	290
Internal Friction Angle (Degree)	47°
Constant "a"(psi)	186.5
Constant "b"(-)	0.69

6. Critical Flow Rate Model

In this section, a tentative model is presented to study the critical flow rate in order to take advantage of sand production while maintain formation stability. Sand production may lead to the change of formation flow parameters such as permeability and porosity and mechanical parameters such as cohesion. It also causes near wellbore stress redistribution. So, sand production is a very complicated process involving both fluid flow and geomechanical problems. In view of this, based on the fluid flow modeling and reservoir geomechanics concept critical flow rate induced sanding will be determined.

In equation (7), it can be seen that the horizontal stress generally can not be changed and Poisson's ratio a well as reservoir rock friction angle are also assumed can not be changed during regular production and sand production. If at a specific time, the average reservoir pressure can not be changed, then the only parameters can be changed are borehole flowing pressure (P_{wf}) and cohesive strength (S_o). P_{wf} can be adjusted by the operator during production and $S_o$can be changed with the amount of sand production. The following relation is assumed between the original formation rock cohesive strength (S_o^o) and the dynamic formation rock cohesive strength (S_o) [10].

$$S_o = S_o^o(1-\phi) \tag{11}$$

For the sandstone formation, an equation developed for estimation of the changes in porosity of sandstone layers due to sand production by Yi (2001) is as following:

$$\phi = S_o^o(1-\phi_o)exp\left(-\lambda v_o^2 t_p\right) \tag{12}$$

By replacing the S_o^o from equation (7) into equation (12), yield

$$Q_o \le \frac{1}{5.615}\sqrt{\ln\left(\frac{C_p}{2\sqrt{2}cos\phi_f(1-\phi_o)}\right)\frac{\left(2\pi h_p R_w\right)^2}{\lambda t_p}} \tag{13}$$

Where

$$C_p = \sqrt{\left(A-P_{wf}\right)^2+\left(B+CP_{wf}\right)^2+(D+EP_{wf})^2} - 3b\left(F+GP_{wf}\right) \tag{14}$$

$$A = 3\sigma_H - \sigma_h - \sigma_v - 2\nu(\sigma_H - \sigma_h)$$

$$B = \sigma_v + 2\nu(\sigma_H - \sigma_h) - B_e P_p$$

$$C = B_e - 1$$

$$D = -3\sigma_H + \sigma_h + B_e P_p \tag{15}$$

$$E = 2 - B_e$$

$$F = \frac{1}{2}\left(3\sigma_H - \sigma_h - B_e P_p\right)$$

$$G = \frac{B_e}{2} + \alpha$$

Where Q_o is the critical oil flow rate (bbl/Day) , h_p is the height of pay zone (ft), t_p is the production time (day), ϕ_o is the initial porosity of formation, R_w is the wellbore radius and other parameters is described in the section 5. From this equation, it can be seen that for given set of parameters such as average reservoir pressure, bottomhole pressure, horizontal stress, poison ratio, cohesive strength and friction angle. Figure 2 plotted the critical flow rate (CFR) for target sandstone layer versus depth.

7. CONCLUSION

In this paper, a tentative model is presented to study the critical flow rate for vertical wells in order to take disadvantage of sand production and the result indicated that in unconsolidated sandstone layers, flow rate plays a key role in instability of these layers.

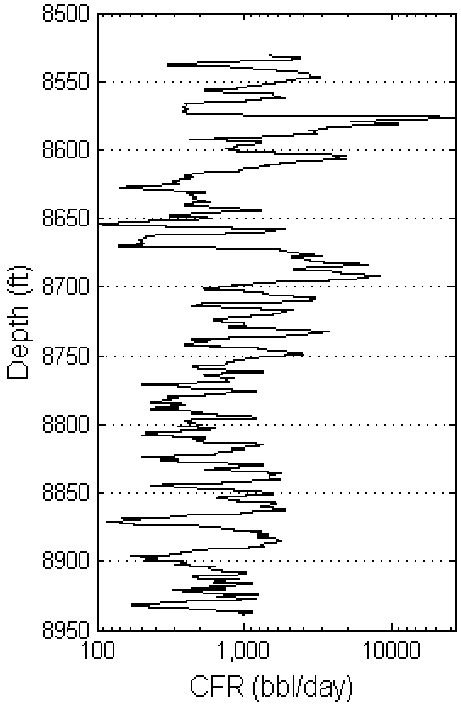

Figure 2: Predicted critical flow rate profile in the target sandstone layer.

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