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Research Paper

# Sand Production Prediction and Well Completion Optimization

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***A b s t r a c t***

Sand production is an important challenge in upstream oil and gas industry, causing operational and safety problems. Therefore before drilling the wells, it is essential to predict and evaluate sanding onset of the wells with the intention of drilling trajectory optimization. In spite of choosing optimized trajectory, in some producing wells by variation of well production condition, sand production may be occurred. So in this situation, appropriate well completion design is crucial. This research considers sanding problems in two steps. At the first stage, an analytical sand prediction model using Mogi-Coulomb failure criterion was presented for determination of maximum sand free drawdown. In this model, by changing the drawdown and wellbore trajectory, sand failure will be predicted by comparing the sand strength to the failure criteria. The results show that in different in situ stress regimes the inclination and azimuth have a significant role in wellbore stability during production. At the second stage, by considering a well with sanding problem, different well completion scenarios were simulated and modelled in order to select the optimum well completion method.

***Keywords:***

*Sanding onset prediction,*
*Failure criteria,*
*Maximum drawdown,*
*Completion optimization.*

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## 1. Introduction

Sometimes in the sandstone reservoir, oil and gas production coincides with movement of unintentional solid particles toward the wellbore which is called sand production. Sand production causes many troubles that cost the oil companies. Therefore, all of the field operator must consider this phenomenon in field development plans to see when and under what situation sand will be produced. By forecasting the drawdown associate with onset of sanding in different well trajectory, the best wellbore trajectory can be determined. In the case of sanding production, different well completion scenarios should be investigate for sand management and selection of the best well completion method.

Mechanical instabilities and sand onset prediction are evaluated in different categories in the literature [1-4]. For sanding onset prediction, it is required to compare stresses around the borehole with rock strength using an appropriate failure criterion. Various 2D and 3D failure criteria have been used in sand onset calculation [5-7]. Mohr-Coulomb is the most commonly applied failure criterion. But onset of sand production cannot be properly predicted by adopting Mohr Coulomb criterion; Because of ignoring the strengthening effect of intermediate principal stress. Numerous studies show that intermediate principal stress has an influence on rock failure [8]. Al-Ajmi and Zimmerman (2005) have developed three dimensions Mogi-Coulomb failure criterion and applied it in stability analysis during drilling condition [9]. After good results of this criterion in stability analysis, this research has applied Mogi-Coulomb failure criterion in sand prediction modeling to obtain maximum sand free drawdown (MSFDD) pressure during production operation in open hole completion. In addition, optimum well trajectory (inclination and azimuth) is obtained for a well in different stress regimes.

## 2. Sand production prediction

Predicting sanding onset required to see, whether condition for wellbore collapse will be fulfilled in production situation or not.

Drilling a well through the formations causes to stress concentration around the borehole that may lead to formation failure. To obtain stresses distribution around the bore hole a constitutive model is needed which linear poro-elasticity is the best one for production condition. Maximum stresses occur in the wellbore wall, Therefore failure is inspected to initiate there. Total stress component at the borehole wall becomes [5]:

$$\sigma_r = p_w \tag{1}$$

$$\sigma_\theta = \sigma_{xx} + \sigma_{yy} - 2(\sigma_{xx} - \sigma_{yy})\cos 2\theta - 4\tau_{xy}\sin 2\theta - p_w + \beta(p_w - p_f)$$

$$\sigma_z = \sigma_{zz} - \upsilon\left[2(\sigma_{xx} - \sigma_{yy})\cos 2\theta - 4\tau_{xy}\sin 2\theta\right] + \beta(p_w - p_f)$$

$$\tau_{\theta z} = 2(\tau_{yz}\cos\theta - \tau_{xz}\sin\theta)$$

$$\beta = \frac{1-2\upsilon}{1-\upsilon}\beta_0. \tag{2}$$

$$\sigma_{xx} = (\sigma_H \cos^2\alpha + \sigma_h \sin^2\alpha)\cos^2 i + \sigma_v \sin^2 i \tag{3}$$

$\sigma_{yy} = (\sigma_H \sin^2\alpha + \sigma_h \cos^2\alpha)$ ; $\sigma_{zz} = (\sigma_H \cos^2\alpha + \sigma_h \sin^2\alpha)\sin^2 i + \sigma_v \cos^2 i$ ;

$\tau_{xy} = \frac{1}{2}(\sigma_h - \sigma_H)\sin 2\alpha \cos i$ ; $\tau_{xz} = \frac{1}{2}(\sigma_H \cos^2\alpha + \sigma_h \sin^2\alpha - \sigma_v)\sin 2i$

$\tau_{yz} = \frac{1}{2}(\sigma_h - \sigma_H)\sin 2\alpha \sin i$ .

Reservoir pressure depletion during production also affects the in situ stresses and cause that horizontal in situ stresses decrease according to the following relations [10].

$$\sigma_H = \sigma_H^0 - \frac{1-2\upsilon}{1-\nu}\beta_0 \Delta p_{dep} \qquad (4)$$

Always principal stresses applied into failure criteria. At production condition usually radial stress is minimum principal stress and two other principal stresses determined according to the following equation [11].

$$\sigma_{1,2} = \frac{1}{2}(\sigma_\theta + \sigma_z) \pm \sqrt{(\sigma_\theta + \sigma_z)^2 + 4\tau_{\theta z}^2} \ . \qquad (5)$$

To predict sanding onset various failure criterion have been developed, among them Mohr Coulomb is much referred and used in practice. According to this criterion at production condition, rock shear strength ($\tau_{Mohr}$) and applied shear stress ($\tau_{Max}$) become:

$$\tau_{Mohr} = C\cos\varphi + \sin\varphi(\frac{(\sigma_1 + \sigma_3)}{2} - p_w) \quad ; \tau_{Max} = \frac{(\sigma_1 - \sigma_3)}{2} . \qquad (6)$$

Where C is rock cohesion strength and $\varphi$ is internal friction angel. Sanding onset happens when applied shear stress ($\tau_{Max}$) exceed rock shear strength ($\tau_{Mohr}$).

In 2005, three dimensions Mogi-Coulomb failure criterion that is naturally extension of Mohr-Coulomb into three dimensions space is developed. This failure criterion has been justified by experimental evidences from triaxial tests as well as polyaxial tests. According to this criterion at production condition, rock shear strength ($\tau_{Mogi}$) and applied shear stress ($\tau_{oct}$) become [9]:

$$\tau_{Mogi} = a + b(\frac{\sigma_1 + \sigma_3}{2} - p_w) \ . \qquad (7)$$

$$\tau_{oct} = \frac{1}{3}\sqrt{(\sigma_1 - \sigma_3)^2 + (\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2} \qquad (8)$$

The strength parameter (a) is related to friction angle and rock cohesion while parameter (b) basically corresponds to friction angle. These parameters could be determined according to Mohr-Coulomb strength parameters:

$$a = \frac{2\sqrt{2}}{3}s_0\cos\varphi; \ b = \frac{2\sqrt{2}}{3}\sin\varphi \ . \qquad (9)$$

In this paper it is assumed that sand production initiates due to formation shear failure around the wellbore. So a wellbore pressure which is named critical bottom hole flowing pressure (CBHFP) can be calculated and maximum sand free drawdown (MSFDD) could be obtained. Regard the fact that radial, tangential and axial stresses are function of wellbore pressure (Pw). Therefore, principal stresses are also function of well pressure. Also these stresses change due to well trajectory and operation condition such as drawdown and depletion. So an iterative loop should be applied to obtain critical bottom hole pressure. In this study a computer program is developed to obtain the critical bottom hole pressure that cause wellbore collapse. This program using several input parameters, including: in situ stresses (vertical stress, maximum and minimum horizontal stresses), rock strength parameters (cohesion, friction angle and Poison ratio), initial and current formation pressure and Biot's poroelastic constant. In production condition wellbore pressure decrease from initial formation pressure until the condition for wellbore collapse satisfied. These analyses have been done for different well inclination ($i = 0$ to $i = 90$) and azimuth ($\alpha = 0$ to $\alpha = 180$) in several cases of in situ stress regimes. Fig. 1 shows the algorithm of the developed program for sanding analysis using the Mogi-Coulomb failure criterion.

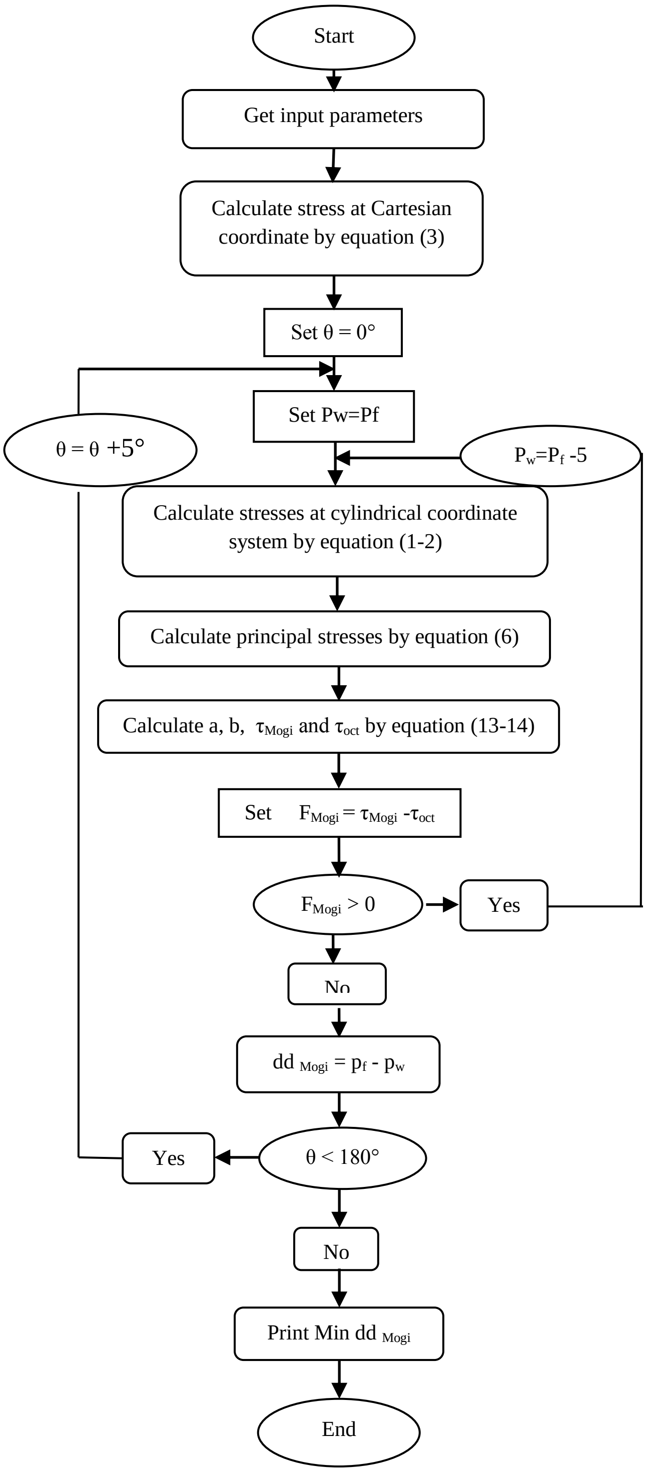


Fig. 1: Sanding Onset Prediction Flowchart According To Mogi-Coulomb Failure Criterion

## 3. Sand management and completion optimization

When the sand prediction model verified probability of encountering sand production, at the next step the operating companies should make decisions about the best approach to optimize well completions and exclude the sand from production or limit the impact of produced sand.

Initially, the question is whether to control or to prevent sand production. Sand exclusion methods may be required when sand production is certain, or when the risk associated with unforeseen sand production is high; for example, in subsea completions or high-rate gas wells. One of a variety of screenless-completion methods may offer the best option when sand production can be avoided or at least limited. Regardless of the method, proper sand management is the vehicle needed to balance sand control with the desired production results through optimized completions. The four main classes of completion are Slotted liners, Pre-packed screens, Wire wrapped screen and Gravel packing. So, in order to optimize well completion, these different well completion scenarios using Prosper software were simulated and modeled in one of Iranian oilfield well with sand production problem.

## 4. Results and discussion

### 4.1. Onset of sanding and Optimum well trajectory

The new sand onset prediction model is used to determine optimum stable well trajectory during production in three different cases of in-situ stress regimes. Table. 1 contains hypothetical input parameters of three different cases for mechanical stability analysis during production condition.

Table. 1: Input Data for Sanding Onset Analysis in Different Stress Regime

| Stress Regime | Normal Fault | Strike Slip | Reverse Fault |
|---|---|---|---|
| **Depth (ft)** | 4500 | 4500 | 4500 |
| **$\sigma_v$ (Psi/ft)** | 1 | 0.9 | 0.7 |
| **$\sigma_H$ (Psi/ft)** | 0.9 | 1 | 1 |
| **$\sigma_h$ (Psi/ft)** | 0.7 | 0.7 | 0.9 |
| **$P_f$ (Psi/ft)** | 0.45 | 0.45 | 0.45 |
| **$\nu$** | 0.3 | 0.3 | 0.3 |
| **$S_0$ (psi)** | 1100 | 1100 | 1100 |
| **Φ (degree)** | 35 | 35 | 35 |
| **$\beta_0$** | 0.9 | 0.9 | 0.9 |

Fig. 2 shows MSFDD pressure of the wells with different inclination and azimuth for a well in normal fault stress regime. It is concluded that the MSFDD pressure of near vertical boreholes are greater than the horizontal boreholes, so boreholes close to vertical direction have less potential for sanding than the horizontal boreholes and almost all the deviated wells. It is also obvious that, drilling parallel to the minimum horizontal stress direction is the best trajectory in this case ($\alpha = 90^\circ$). These results match a study which evaluated sand production in a South East Asia field with normal fault stress regime [8].

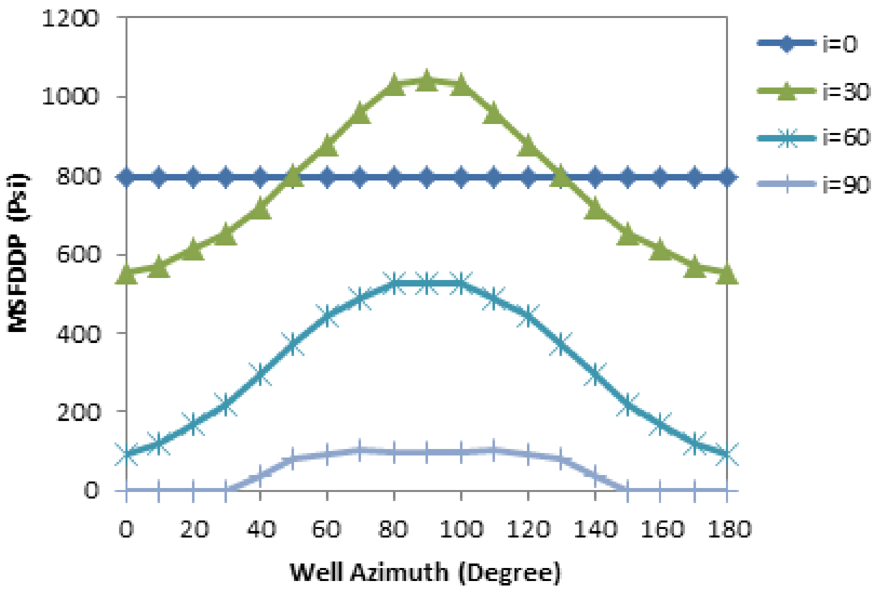


Fig. 2: MSFDD Pressure of Wells with Different Trajectory in Normal Stress Regime

Fig. 3 shows variation of MSFDD pressure for a well in strike slip stress regime. It illustrates that horizontal boreholes have less potential for sand production than the vertical and deviated boreholes in all directions. In this case the best direction is a horizontal borehole closes to the maximum horizontal stress direction.

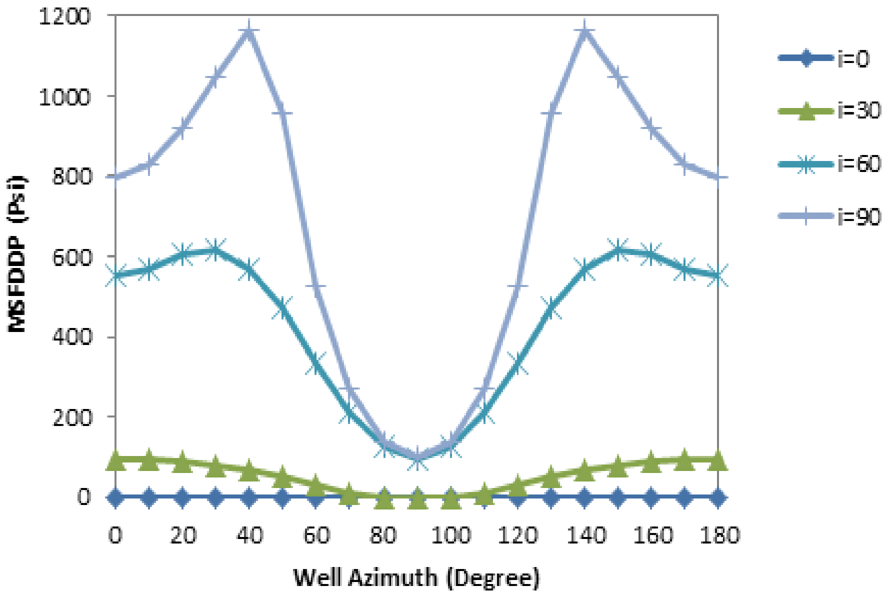


Fig. 3: MSFDD Pressure of the Wells with Different Trajectory in Strike Slip Regime

Fig. 4 demonstrates sand production in a formation with the reverse fault regimes. It shows that in production situation the highly inclined wells are more stable than the vertical ones. Also, the optimum direction is parallel to the maximum principal in situ stress, $\sigma_H$ and the largest MSFDD pressure is associated with (i = 60º) borehole in this case. Zero MSFDD means sand produce at start of well production and sand control devices need to be installed.

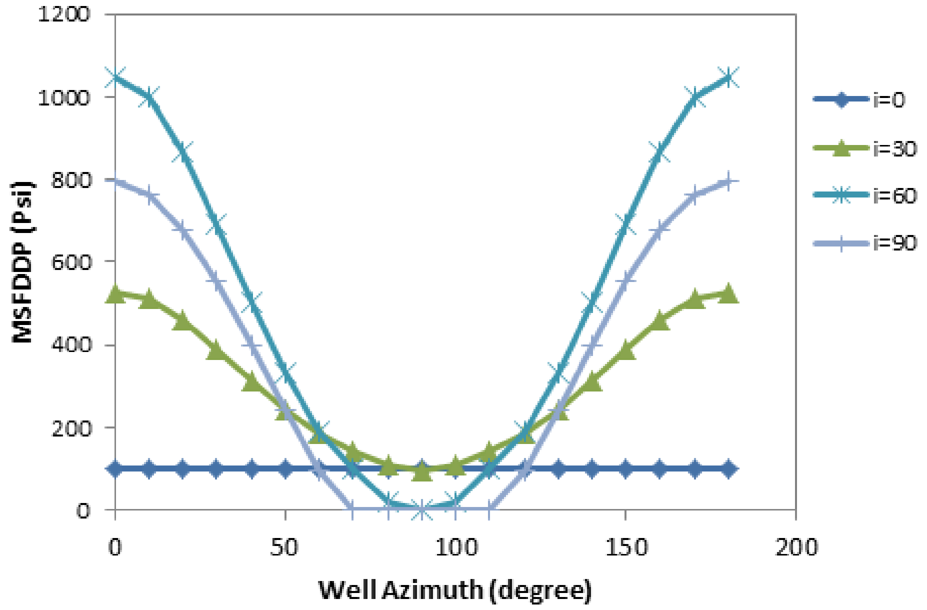


Fig. 4: MSFDD Pressure of the Wells with Different Trajectory in Reverse Stress Regime

Fig. 5 exhibits MSFDD pressure as function of inclination for three different stress regimes at same azimuth, (α = 30º). It is often assumed that higher deviated wellbore cause sand potential to be increased. From this figure, it can be illustrated that this assumption is not always true. It is concluded that, the risk of sand production increases with increasing the borehole inclination only in normal fault stress regime. But, in strike slip and reverse fault stress regime increasing the borehole inclination decreases the sand potential. In addition it reveals that MSFDD in the reverse fault is less sensitive to the inclination than normal fault and strike slip stress regimes.

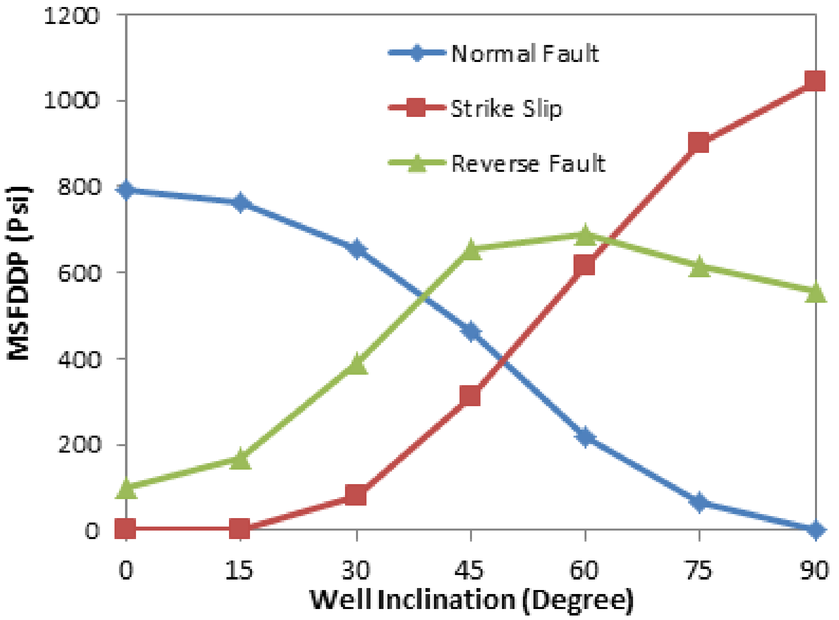


Fig. 5: MSFDD Pressure for Three Different Stress Regimes with Different Well Inclination

During production, pore pressure decreases and then in situ stresses and borehole stresses change as result of reservoir depletion. So a well which is initially produces without sand might start to sand production after some time. In order to investigate the effect of depletion on sand production, the model was run for different reservoir pressure (Fig. 6). In this Figure, the horizontal axis shows the reservoir pressure and the vertical one is bottom hole flowing pressure (BHFP). The three colored lines show reservoir rock with three different rocks strength. The vertical distance between line of each rocks strength and the line with slope 1 (violet one) shows amount of sand free drawdown at specific reservoir pressure. It reveals that increasing amount of depletion decrease the maximum sand free drawdown or increase sand potential. Also this figure demonstrates that reservoirs which have more rock strength could produce with higher sand free drawdown for longer period.

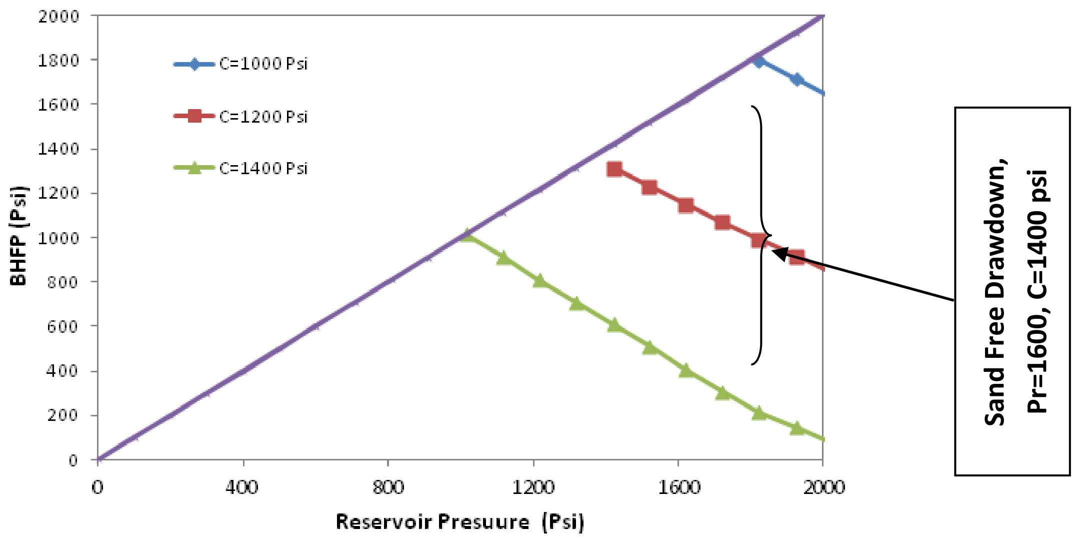


Fig. 6: Sand Free Drawdown Pressure for Three Different Reservoirs Rock Strength

### 4.2. Completion Optimization

In this section, a well with sanding problem which is located in one of the Iranian oilfield have been studied. The four main available sand control completions which have been used in this field are Gravel pack, Pre-packed screen, Wire wrapped screen and Slotted liner. The critical and guide parameters for optimizing and choosing the most appropriate completion type are: amount of well flow rate and pressure loss and the best well completion scenarios is the one in which causes highest well flow rate and lowest pressure loss. These four main completion methods were simulated by Prosper software.

Fig. 7, Fig. 8, Fig. 9 and Fig. 10 show the simulation results for Gravel packing, Pre-Packed screen, Slotted liner and Wire wrapped screen respectively. In these figures, the blue points show inflow performance relationship, the green points show pressure loss due to sand control and the red points show total pressure loss. According to these figures, Wire wrapped screen lead to the lowest amount of pressure loss compare to the others; the highest pressure loss occurs in Slotted liner. Moreover Table. 2 shows amount of well flow rate in different sand control completion which shows wire wrapped screen results in maximum flow rate whereas slotted liner causes minimum well flow rate.

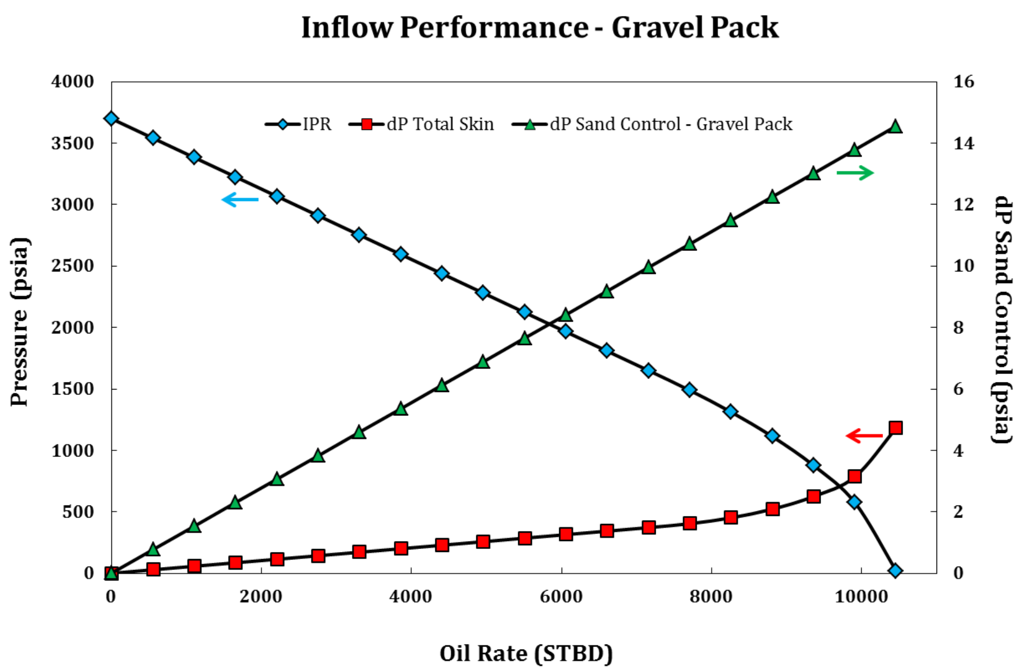


Fig. 7: Inflow Performance Relationship and Pressure Drops in the Case of Gravel Pack

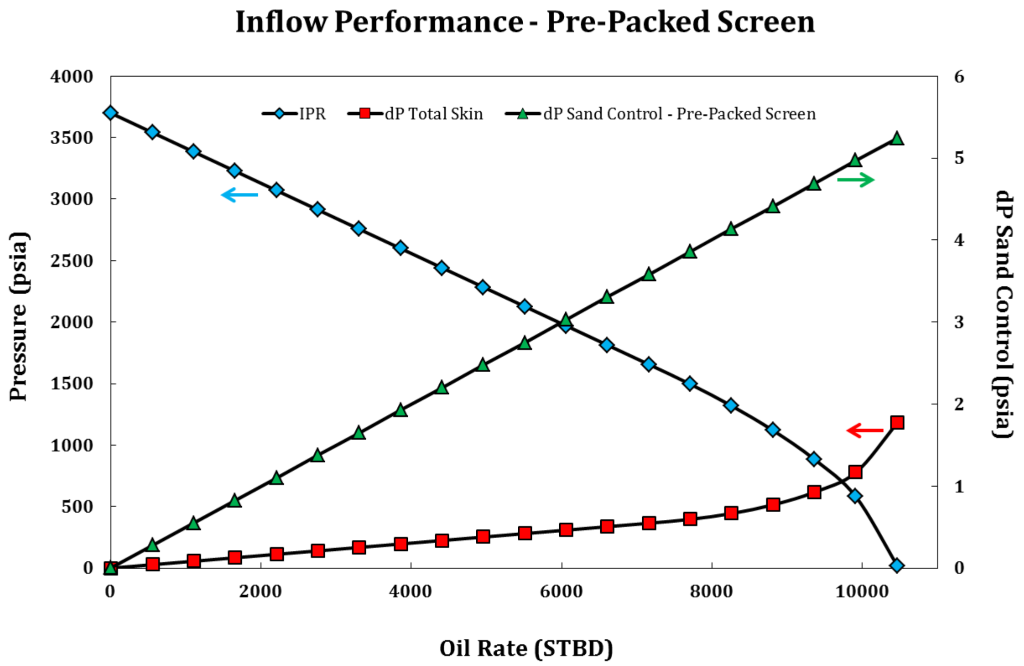


Fig. 8: Inflow Performance Relationship and Pressure Drops in the Case of Pre-Packed Screen

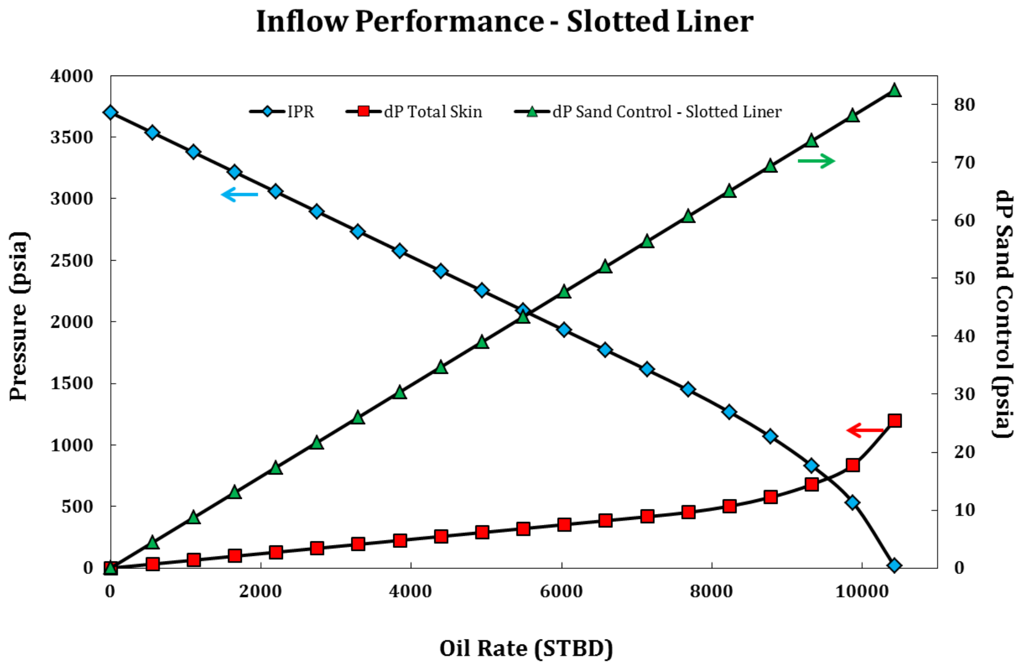


Fig. 9: Inflow Performance Relationship and Pressure Drops in the Case of Slotted Liner

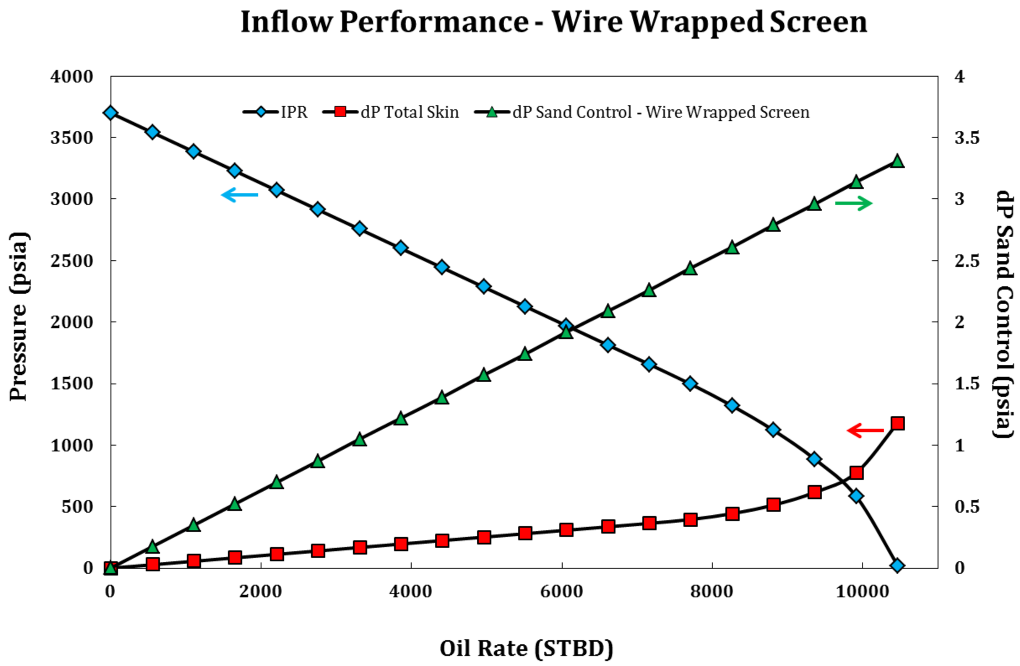


Fig. 10: Inflow Performance Relationship and Pressure Drops in the Case of Wire Wrapped Screen

Table. 2: Well Flow Rate in Different Sand Control Completion Scenarios

| **Well Completion Scenarios** | Well Flow rate (STBD) |
| --- | --- |
| **Wire wrapped screen** | 2088 |
| **Gravel pack** | 1923 |
| **Pre-packed screen** | 2001 |
| **Slotted liner** | 1804 |

## 5. Conclusions

In this study an analytical model was presented to determine maximum drawdown pressure for sand production prevention in open hole wells. In addition, by considering a well with sanding problem, different well completion scenarios were simulated and modeled in order to select the optimum well completion method.

The following conclusions can be achieved from this research:

**i.** In the case of normal fault stress regime, drilling in direction of minimum horizontal stress is the best direction for preventing sand production.

**ii.** In strike-slip and reverse fault stress regimes, drilling in direction of minimum horizontal stress provide maximum sand production potential.

**iii.** Drilling near vertical boreholes will minimize the sand potential only in normal fault stress regimes and highly deviated wells are better to prevent sand production in other two stress regimes.

**iv.** Depletion lead to increase sanding potential because it changes effective in situ stresses.

**v.** Well completion optimization in one of Iranian oil well reveals that wire wrapped screen results in maximum flow rate and minimum pressure loss while slotted liner causes minimum well flow rate and maximum pressure loss.

## NOMENCLATURES

| | |
|---|---|
| UCS | Uniaxial Compressive Strength, (Psi) |
| MSFDDP | Maximum Sand Free Drawdown Pressure, (Psi) |
| $P_w$ | Wellbore Pressure, (Psi) |
| $P_f$ | Current formation Pressure, (Psi) |
| $\Delta p_{dep}$ | Depletion pressure, (Psi) |
| $\theta$ | Angular position around the wellbore circumference, (Degree) |
| C | Rock cohesion strength, (Psi) |
| $\varphi$ | Rock friction angle, (Degree) |
| $\eta$ | Modified Lade friction parameter, dimensionless |
| $\beta_0$ | Biot poroelastic constant, dimensionless |
| $\upsilon$ | Poisson ratio, dimensionless |
| $\sigma_1$, $\sigma_2$, $\sigma_3$ | Principle stresses, (Psi) |
| $\sigma_H$, $\sigma_h$ , $\sigma_v$ | Maximum, minimum horizontal and vertical stresses, (Psi) |
| $\sigma_r$, $\sigma_z$, $\sigma_\theta$ | Radial, axial and tangential stress, (Psi) |
| $\tau_{xy}$, $\tau_{xz}$, $\tau_{yz}$ | Shear stresses at wellbore coordinate system, (Psi) |

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