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ESTABLISHMENT OF A SAND PRODUCTION PREDICTION MODEL FOR VERTICAL WELLBORES USING THE THREE DIMENSIONAL HOEK–BROWN CRITERION

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Abstract

Sand production is a critical issue in oil and gas industry. During the production of a well, sand production may have negative consequences such as risk of well failure, erosion of pipelines and surface facilities and need for sand separation and disposal.

Knowing the conditions for the onset of sand production allows optimizing sand free production and, eventually, avoiding or delaying the use of sand control methods.

The objective of this paper is to present a new 3D analytical model that can predict sanding onset from vertical openhole wellbores. This model estimates the critical wellbore pressure below which sand production is expected. The three-dimensional Hoek–Brown strength criterion developed by Zhang and Zhu conjunction with linear poroelastic constitutive model is utilized to develop the model. The analytical model is applied to real field case from published literature in order to verify the applicability of the developed model. The results show that a good agreement is reached between predicted and field measured critical wellbore flowing pressure. Furthermore, the developed model can be utilized for cased wellbores as an approximation. Such predictions are necessary for providing technical support for sand control decision-making and predicting the production condition at which sand production occurs.

Keywords: Sand production; Hoek–Brown; Poroelastic constitutive model; Openhole wellbores; wellbore flowing pressure.

1. Introduction

For a long time sand production has been viewed as a cost source and a safety hazard for the oil and gas industry. [1]. In the petroleum industry, the term "sand production" refers to the production of solid particles together with the formation fluids. This phenomenon is common mainly in weak sandstone reservoirs and is a possible consequence of the degradation of the mechanical properties of the rock surrounding the wellbore caused by drilling, completion, and production operations particularly, during the production phase, the decrease of pore pressure causes a concentration of stresses around the wellbore and the perforation tips which, in turn, can lead to the failure of the rock. When the right conditions are met, e. g. production rates sufficiently high, then the failed rock can be mobilized and the fluid flow can drag to the surface grains, particles or aggregates of the damaged rock [2].

Sanding related problems can reduce the oil production, increase well completion and operating expense, erode downhole and surface facilities, and even cause well failure. Therefore, it is crucial to know whether and when the sand production would occur and how severe it will be, so corresponding measures could be taken to guarantee the oil production and maximize the project economics [3].

Sand production mechanisms can be summarized into the following points [4]: (1) Shear failure induced by fluid pressure drawdown can lead to the breaking of sand grain bonds and the alteration of the material's mechanical properties; (2) Tensile failure caused by high hydrocarbon production rates can lead to dilation of solid skeleton and the loss of solid particles mechanical interactions through disaggregation; (3) High stresses due to completion cause the formation to fail (in compression) whereas fluid viscous drag forces bring the failed materials from the perforation tunnels into the wellbore.

There are many factors that must be considered to obtain a comprehensive understanding of how and why sand production occurs and such factors include: (1) Geological factors (2) Rock composition (3) Mechanical factors (4) Drilling practices (5) Production operations [5].

In the past decades, a number of approaches have been developed to predict the sand production. In general, these approaches can be categorized into three basic groups: (1) Empirical methods, (2) Laboratory evaluation, and (3) Theoretical modeling including analytical and numerical methods [2]. Empirical methods are quite simple and usually based on the field observations. The correlations between sand production and field data such as log data could be established [6]. Laboratory experiments are carried out to disclose the possible sanding mechanism and understand the influence of the field and operational parameters [7-8]. Theoretical modeling is based on the perforation stability analysis and requires the mathematical formulation of the sand failure mechanism such as compressive failure, tensile failure and erosion. Numerical models allow the analysis of all the involved physical phenomena during the whole life of the well and with the desired level of detail [9].

Even though a numerical model, such as finite element model, is more general, analytical or semi-analytical models may be more convenient and easier to use under special conditions. Besides, an analytical model is always useful to verify numerical models [10]. Analytical models usually employ a poroelastic solution to calculate the stresses at the borehole/perforation wall as a function of the in situ stresses and pore pressure and the applied depletion and drawdown [11].

Numerous sand prediction methods have currently been employed to assist in designing sand-prevention devices for completion and in determining the maximum depletion rate for a sand-free production. For predicting the critical drawdown pressure at the maximum bottomhole flowing pressure under the simple configurations, analytical methods are popular [12-15].

Zhang and Zhu developed a 3D Hoek-Brown strength criterion for rocks. This criterion properly considers the effect of the intermediate principal stress, neither ignoring the intermediate principal stress effect as the Mohr-Coulomb criterion does nor over-considering the intermediate principal stress effect as the Drucker-Prager criterion does. The 3D Hoek-Brown strength criterion also has the advantage over other 3D strength criteria in that it uses the same input parameter as the most widely used Hoek–Brown criterion in rock mechanics and rock engineering [16].

In this paper, the 3D Hoek-Brown strength criterion developed by Zhang and Zhu [16] is used to establishment of sanding onset prediction model. Furthermore, this analytical model is applied to field data in order to verify the applicability of the developed model.

2. Stress concentration around a vertical wellbore at production condition

Assuming that the formation behaves like brittle rock, stability analysis in production condition, required to compare principal stress around the borehole with an appropriate failure criterion to see if conditions for a wellbore collapse will be fulfilled or not. Based on linear elasticity, maximum stresses, occur in the wellbore wall. Therefore, sanding is expected to initiate at the borehole wall [17] (Fig. 1).

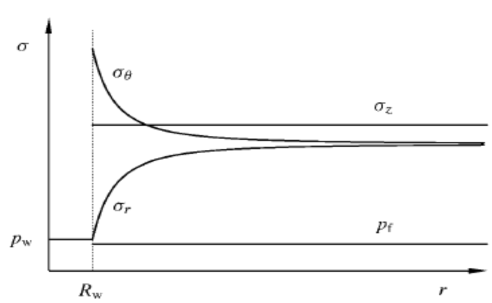

Fig. 1. Stresses around a vertical borehole in a linear elastic formation [13].

The stress concentration around a vertical well drilled in an isotropic, elastic medium under anisotropic in-situ stress condition (maximum and minimum horizontal stresses are different) is described by the Kirsch equations. The general expressions for the maximum effective stresses at the vertical wellbore wall in the production situation are [13]:

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

$$\sigma'_\theta = 3\sigma'_H - \sigma'_h - P_{wf} + B_e(P_{wf} - P_{pf}) - \alpha P_{wf}$$

$$\sigma'_z = \sigma_v + 2\nu(\sigma'_H - \sigma'_h) + B_e(P_{wf} - P_{pf}) - \alpha P_{wf} \quad (1)$$

where σ'_H and σ'_h are the maximum and minimum horizontal stresses at current production condition, respectively; σ_v is the vertical stress; α is Biot's coefficient; ν is the Poisson's ratio; σ'_r is the effective radial stress; σ'_θ is the effective tangential (hoop) stress; σ'_z is the effective axial stress induced around the wellbore; P_{wf} is the bottomhole flowing pressure; P_{pf} is the farfield pore pressure and B_e is the poroelastic stress coefficient defined as

$$B_e = \frac{1-2\nu}{1-\nu}\alpha \quad (2)$$

The effect of reservoir pressure decline due to production can be accounted by updating the in-situ stresses. For a laterally large reservoir compared to its thickness, the change in vertical stress is considered negligible and therefore it is usually kept constant [18]. The maximum and minimum horizontal stresses are updated as follows, respectively:

$$\sigma'_H = \sigma_H - B_e \Delta P_r \quad (3)$$

$$\sigma'_h = \sigma_h - B_e \Delta P_r \quad (4)$$

where: $\Delta P\_r = P\_ri - P\_rc$

where σ_H and σ_h are the maximum and minimum horizontal stresses; respectively, and P_{ri} and P_{rc} are the initial and current reservoir pressures, respectively.

3. Three-dimensional Hoek-Brown strength criterion

A great number of rock strength criteria have been proposed over the past decades. Of these different strength criteria, the Hoek-Brown strength criterion has been used most widely, because: (1) it has been developed specifically for rock materials and rock masses; (2) its input parameters can be determined from routine unconfined compression tests, mineralogical examination, and discontinuity characterization; and (3) it has been applied for over 20 years by practitioners in rock engineering, and has been applied successfully to a wide range of intact and fractured rock types . For intact rock, the Hoek–Brown strength criterion may be expressed in the following form [19-20].

$$\sigma'_1 = \sigma'_3 + \sigma_{ci}\left(m_i \frac{\sigma'_3}{\sigma_{ci}} + 1\right)^{0.5} \quad (5)$$

where σ_{ci} is the Uniaxial Compressive Strength of intact rocks; σ'_1 and σ'_3 are respectively the major and minor effective principal stresses, and m_i is a material constant for the intact rock, which depends upon the rock type (texture and mineralogy).

For jointed rock masses, the Hoek–Brown strength criterion can be expressed as follows [23]

$$\sigma'_1 = \sigma'_3 + \sigma_c\left(m_b \frac{\sigma'_3}{\sigma_c} + s\right)^{a} \quad (6)$$

Where $m_b = m_i \exp\left(\frac{GSI-100}{28-14D}\right)$ $\quad s = \exp\left(\frac{GSI-100}{9-3D}\right)$

$$a = 0.5 + \frac{1}{6}\left[\exp\left(\frac{-GSI}{15}\right) - \exp\left(\frac{-20}{3}\right)\right] \quad (7)$$

The parameter m_b is a reduced value of m_i, which accounts for the strength reducing effects of the rock mass conditions defined by Geological Strength Index (GSI). Adjustments of 's' and 'a' are also done according to the GSI and D values [24]. GSI was estimated from the chart of Marinos *et al.* [25] (Fig. 2). D is a factor which depends upon the degree of disturbance to which the rock mass has been subjected by blast damage and stress relaxation. It varies from 0 for undisturbed in situ rock masses to1 for very disturbed rock masses [23].

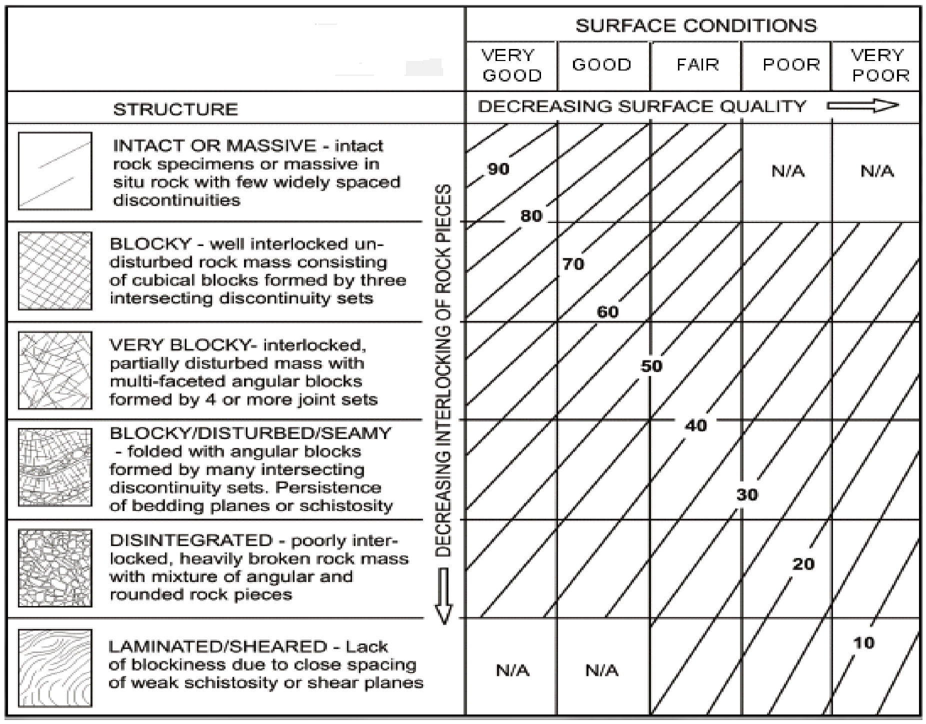

Fig. 2 GSI chart for jointed rocks [25]

As can be seen from above, the Hoek–Brown strength criterion does not take account of the influence of the intermediate principal stress. Much evidence, however, has been accumulating to indicate that the intermediate principal stress does influence the rock strength in many instances [16, 26-28]. Zhang and Zhu [16] proposed a 3D version of the original Hoek–Brown strength criterion for rock mass (Eq. (6) with a=0.5):

$$\frac{9}{2\sigma_c}\tau_{oct}^2 + \frac{3}{2\sqrt{2}}m_b\tau_{oct} - m_b\sigma_{m,2} = s\sigma_c \quad (8)$$

where $\sigma'_{m,2}$ and τ_{oct} are, respectively, the effective mean stress and the octahedral shear stress defined by

$$\sigma'_{m,2} = \frac{\sigma'_1 + \sigma'_3}{2} \quad (9)$$

$$\tau_{oct} = \frac{1}{3}\sqrt{(\sigma'_1 - \sigma'_2)^2 + (\sigma'_2 - \sigma'_3)^2 + (\sigma'_3 - \sigma'_1)^2} \quad (10)$$

4. Building the sanding onset prediction model

Drilling the wellbore or creating any cavity like perforations, changes the stress pattern in the medium around the cavity. Increase of drawdown augments effective stresses in an interval around the wellbore. This is attributed to the fact that pore pressure recovers much more slowly compared to total stresses. Therefore, shear stresses increase around the cavities once higher drawdowns are used. In this respect, acts depletion very similarly to drawdown in increasing shear stresses around the cavities. Shear failure induced by fluid pressure drawdown takes place once shear stresses exceed limit shear strength of the intact rock and can lead to the breaking of sand grain bonds and the alteration of the material's mechanical properties. Shear failure mechanism is mainly active around the cavities where two major criteria are fulfilled. First, shear stresses are very high and second, differential deformations are possible [9]. Knowing the conditions for the onset of sand production allows optimizing sand free production and, eventually, avoiding or delaying the use of sand control methods.

Fig. 1 shows that σ'_r will have the lowest value at the borehole wall and will never exceed σ'_θ and σ'_z even away from the wellbore wall. It is also seen in Fig. 1 that the tangential stress σ'_θ has the highest value at the wellbore wall. In other words, the stress concentration around the wellbore circumference is mainly dominated by σ'_θ. Therefore, the common scenario in the field is when $\sigma'_\theta \geq \sigma'_z \geq \sigma'_r$ [29]. To predict the well pressure at which sanding will occur the stress equations at the borehole wall must be compared against the failure criterion. Introducing equations of effective induced stresses around the vertical wellbore (Eqs. (1)) into 3D Hoek-Brown criterion (Eq. (8)) when $\sigma'_\theta \geq \sigma'_z \geq \sigma'_r$ gives

$$(P_4)P_{wfc}^4 + (P_3)P_{wfc}^3 + (P_2)P_{wfc}^2 + (P_1)P_{wfc} + P_0 = 0 \quad (11)$$

where P_{wfc} is the critical sanding onset pressure will be the lowest of the four roots of the above equation. The constants P_4, P_3, P_2, P_1 and P_0 are as follows:

$$P_4 = I^2$$

$$P_3 = 2IJ$$

$$P_2 = J^2 + 2IK - (1 + (\mathrm{B_e} - 1)^2 + (2 - \mathrm{B_e})^2)$$

$$P_1 = 2JK - G$$

$$P_0 = K^2 - H$$

$$G = -2\big(3\sigma_H - \sigma_h - \sigma_v - 2\nu(\sigma_H - \sigma_h)\big) + 2\big(\sigma_v + 2\nu(\sigma_H - \sigma_h) - \mathrm{B_e P_p}\big)(\mathrm{B_e} - 1) + 2\big(-3\sigma_H + \sigma_h + \mathrm{B_e P_p}\big)(2 - \mathrm{B_e})$$

$$H = (3\sigma_H - \sigma_h - \sigma_v - 2\nu(\sigma_H - \sigma_h))^2 + (\sigma_v + 2\nu(\sigma_H - \sigma_h) - \mathrm{B_e P_p})^2 + (-3\sigma_H + \sigma_h + \mathrm{B_e P_p})^2$$

$$I = \frac{4(1 + (\mathrm{B_e} - 1)^2 + (2 - \mathrm{B_e})^2)}{\sigma_c m_b^2}$$

$$J = \frac{4}{m_b}(-2\alpha + \beta) + \frac{8G}{m_b^2}$$

$$K = \frac{-4D}{m_b} + \frac{4H}{m_b^2} \quad (12)$$

5. Model verification

The sand production prediction model presented in this paper is verified in a field scale using the case study presented by Yi *et al.* [30]. A vertical well (called Well A) drilled and completed in a sandstone formation in one of the fields located in the Northern and Central Adriatic Sea. The Northern and Central portions of the Adriatic Sea stretching from the gulf of Venice to Ancona make up a single geological unit called the Northern Adriatic Basin (Fig. 3) Geological studies indicate that this basin is a typical case of normally compacted stratigraphic sequences. The strength of the reservoir rocks results exclusively from the compaction of the sand grains and was found to be strongly correlated to depth as a direct consequence of burial.

Figs. 4 and 5 present the porosity, permeability, Uniaxial Compressive Strength (UCS), pore pressure and in-situ stresses data for well A. This well is cased and perforated from 8453 ft to 8458 ft. The geomechanical properties of this target interval are listed in Table 1.

Fig. 3. The Northern Adriatic Basin [30-31]

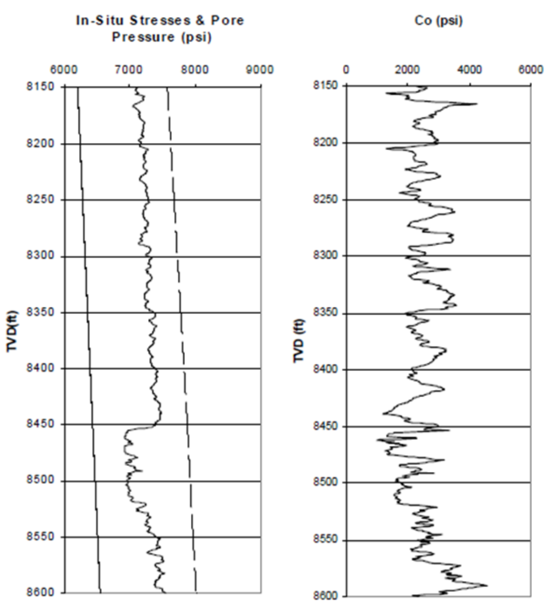

Fig. 4 Logging data for well A [30]

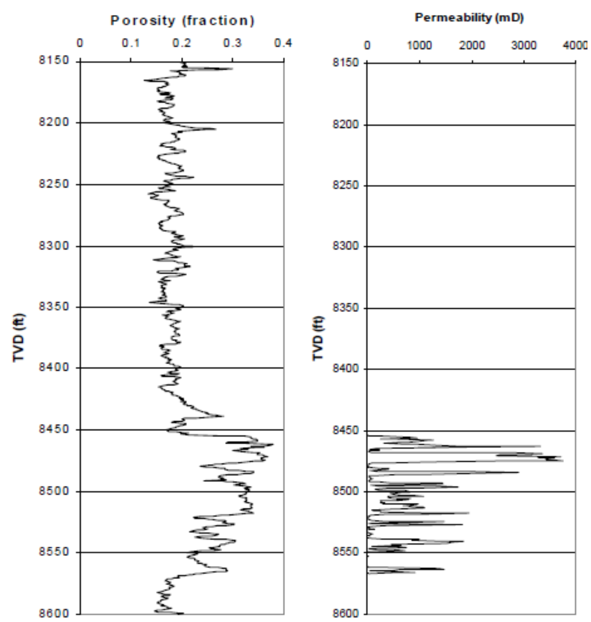

Fig. 5 Logging data for well A (Continued)

Table 1 Geo-mechanical properties of the target interval

Vertical Stress (σ_v)	7700 psi	Farfield Pore Pressure (Ppf)	6400 psi
Maximum Horizontal Stress (σ_H)	7000 psi	UCS (σ_c)	2200 psi
Minimum Horizontal Stress (σ_h)	7000 psi	mi	17
Biot's Coefficient (α)	0.8	D	0.9
Poisson's Ratio (ν_s)	0.3	GSI	45

Field data indicates that sand production occurs at P_{wf}=5486 psi and average reservoir pressure P_r =5508 psi. Fig. 6 shows the predicted and field measured wellbore flowing pressure at sanding onset assuming shear stress induced sanding (real field measured critical P_{wf} is 5486 psi). This figure indicates that a good match between predicted and field-reported sanding wellbore pressures is reached assuming shear-failure induced sanding based on the 3D Hoek-Brow criterion.

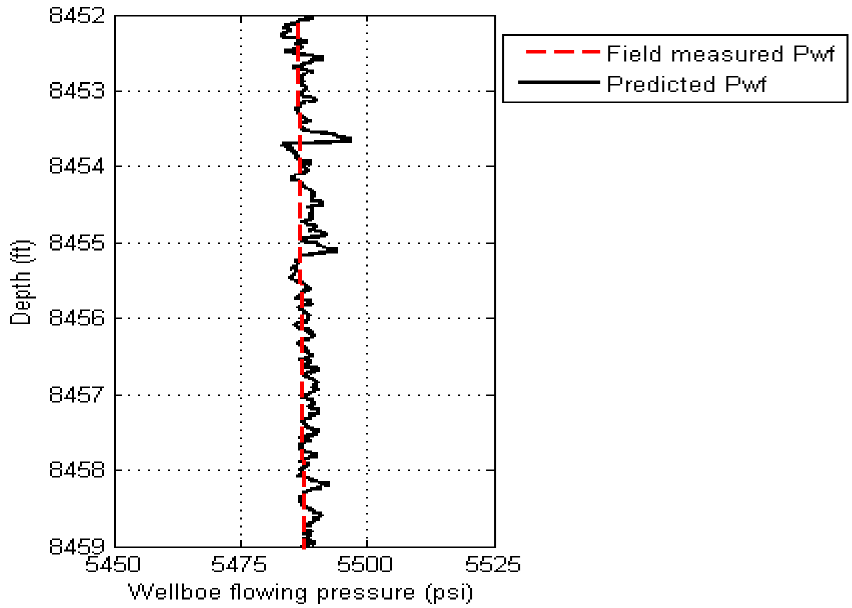

Fig. 6 Predicted and field measured wellbore flowing pressure at sanding onset assuming shear stress induced sanding

6. Conclusions

This paper presented a new 3D analytical model that can predict sanding onset from vertical openhole wellbores based on the 3D Hoek-Brown strength criterion developed by Zhang and Zhu (2007). The 3D Hoek-Brown model properly considers the effect of the intermediate principal stress and can predict the strength of rocks with good accuracy.

This study indicated that the predicted model results agreed well with the actual field observation. The developed model can be utilized for prediction of sanding from cased wellbores as an approximation. This has been proved by a field case study for a cased and perforated well.

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