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RESEARCH PAPER

Geomechanical Sanding Prediction in Oil Fields by Wellbore Stability Charts

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Abstract

Sand production is a universally encountered issue during the exploration of unconsolidated sandstone reservoirs particularly during production. The production of sand particles with the reservoir fluids depends on the stress around a wellbore and the properties of the reservoir rocks and fluids. Therefore, it is crucial to predict under what production conditions sanding will occur and when sand control is needed to come up with the optimal field development plan. This paper presents new geomechanical stability charts for Oman that have been generated to predict sand production in sandstone formations during the production process. The produced stability charts simplified the complicated task of geomechanical analysis, and they are ready for direct applications by petroleum engineers with no need to be specialized in rock mechanics. This was achieved by utilizing a three-dimensional model which was previously justified. The applied model utilized the linear poroelastic constitutive model for the stresses around a borehole in conjunction with Mogi-Coulomb law to predict the failure of sandstone formations. In this work, moreover, the optimum well trajectories for Omani oil fields are reported.

Keywords:
Critical Drawdown Pressure,
Mogi-Coulomb Criterion,
Optimum Well Path,
Sand Production,
Wellbore Stability

Introduction

The geomechanical instability usually occurs as a result of drilling, production operation, and reservoir management activities where the induced *in situ* stresses result in exceeding the *in situ* strength of the formation. In particular, during the production phase, the decrease of pore pressure causes a concentration of stresses around the wellbore and perforation tips which, in turn, can lead to the failure of the rock. From the phenomenological viewpoint, sand production can occur when the formation does not present sufficient strength to resist destabilizing forces generated during the flow of reservoir fluid. It has been estimated that about 70% of the world's oil and gas reserves are found in weakly-consolidated or non-consolidated strata [1-3].

To minimize the risk of sand production, numerous strength criteria have been proposed besides the constitutive law to calculate the minimum mud pressure required for ensuring wellbore stability and to study the optimal well trajectory [4]. The two most commonly used strength criteria in wellbore stability analysis are the Mohr-Coulomb criterion and the Drucker-Prager criterion [5,6]. These failure criteria, however, are generally conservative or optimistic in stability modeling, which can be adjusted by using the Mogi-Coulomb criterion instead [7]. The comparison of the Mogi-Coulomb criterion with other failure criteria had been reported in the literature in several works [8-10].

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This study has utilized a model where the three-dimensional Mogi-Coulomb failure criterion and a linear-poroelastic constitutive model for stresses around boreholes are applied. The work has been limited to fields in normal fault (NF) stress regimes as they are the common situation for Omani sandstone formations. The applied stability model was first developed by Al-Ajmi [7] to evaluate the collapse pressure during drilling. Then, Al-Shaaibi [11] modified the stability model to estimate sanding critical pressure during production. The stability model had been verified by using real case studies where the results agreed with the actual field observations for the following fields [7,11]:

- Cryus reservoir in the UK Continental Shelf [12]
- Pagerungan Island Gas field, north of Bali, Indonesia [13]
- Wanaea oilfield in the Northwest Shelf of Australia [14]
- The ABK field [15]
- Offshore field introduced by Awal and co-workers [16]
- Sandstone formation field introduced by Yi and co-workers [17,18]
- Sandstone formation field introduced by Ewy [19]
- Omani oil field [11]

Sand Production Prediction Technique

Input parameters to develop the stability charts

The utilized stability model had been written as a Mathcad program due to its simplicity in use. The applied model requires defining the following input parameters: (1) the depth of the studied formation, (2) the gradients of pore pressure (P_o) and *in situ* stresses, (3) the cohesion (c), friction angle (ϕ), Poisson's ratio (ν) and Biot's coefficient (α_B), and (4) the borehole azimuth and deviation. Generally, the wellbore stability analysis is complicated and needs specific conduction and study for a field. The challenge here is how to summarize typical field conditions in Oman in a simple way to generate ready-made charts for direct applications in the country.

According to Al-Ajmi and Al-Harthi [20], the maximum horizontal stress (σ_H), cohesion and friction angle of the rock formation are the most critical factors in wellbore stability analysis (see Fig. 1). These three input parameters are considered variable in the study to cover their high impact. For simplicity, the pore pressure, the vertical stress (σ_v) and Poisson's ratio are kept constant due to their low impact in wellbore stability. Similarly, the Biot's coefficient is also kept constant at a value of 1 to simplify the analysis. Furthermore, the fact that the ratio of the maximum horizontal stress to the minimum horizontal stress (σ_h) is globally equal to 1 to 2, and isotropic horizontal stress scenario is rarely encountered in oil fields are considered. In Oman, the maximum ratio of σ_H/σ_h is equal to 1.12 and the minimum horizontal stress has a general range of 0.7-1.2 psi/ft [21]. Considering the global and local features of the field stresses, the common strength parameters of sandstone reservoir and classifying all variables in four levels, the stability charts are established using the following input data:

- σ_H (Psi/ft) = 0.75, 0.80 (with σ_h = 0.7 Psi/ft); and σ_H = 0.85, 0.90 (with σ_h = 0.8 Psi/ft).
- c (Psi) = 500, 1000, 1500, 2000.
- ϕ (Degrees) = 25, 30, 35, 40.
- Constant inputs: P_o = 0.45 Psi/ft, σ_v = 1.0 Psi/ft, ν = 0.2 and α_B =1.

The suggested input values are also within the range of the values which had been reported for sandstone formation in several here [4,8,22-28]

With respect to the depth, the sandstone formations in Oman exist at a depth of 3000-9000 ft. Therefore, the wellbore stability study is conducted every 1000ft in this common depth range. In this way, for every studied depth level, there are four different scenarios for the horizontal stresses with four different levels of cohesion and friction angle as presented in Table 1. This will result in generating 64 stability charts for each studied depth to cover all possibilities.

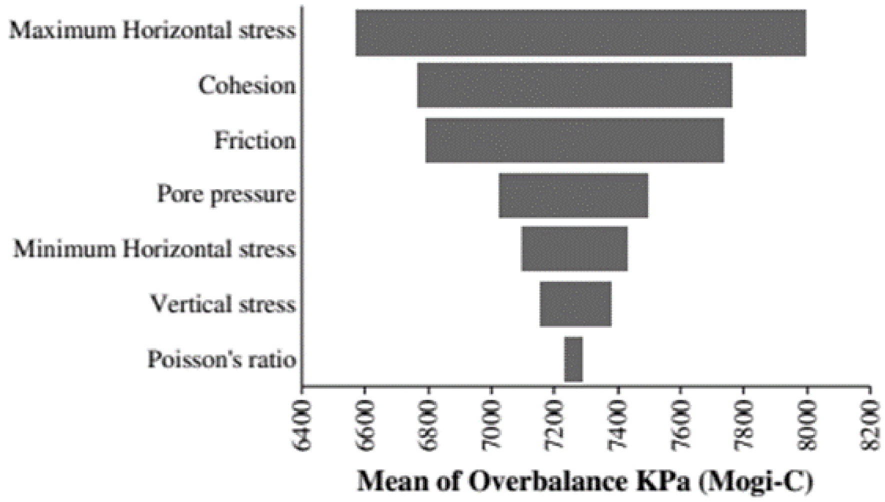

Fig. 1. Tornado diagram for Mogi-Coulomb criterion shows the sensitivity analysis in NF stress regime [20]

Table 1. Scenarios for the model input parameters

Scenario Number	σ_H (Psi/ft)	σ_h (Psi/ft)	c Psi	ϕ Degrees
1	0.75	0.7	500	
			1000	
			1500	25,30,35,40
			2000	
2	0.8	0.7	500	
			1000	
			1500	25,30,35,40
			2000	
3	0.85	0.8	500	
			1000	
			1500	25,30,35,40
			2000	
4	0.9	0.8	500	
			1000	25,30,35,40
			1500	
			2000	

In the developed stability charts, the well pressures are estimated as a function of well inclinations (i) and azimuths (α). The angles of the azimuths are measured with respect to the direction of the maximum horizontal stress. Therefore, for a well drilled parallel to σ_H, the azimuth value is considered to be equal to 0°. Furthermore, due to the symmetry of the wellbore in the stability analysis and to simplify the work, the well azimuths have been demonstrated in the stability charts by the following angles:

- $\alpha 1$ represents the azimuth of 0^o, $360^{o,}$ and 180^o.
- $\alpha 2$ represents the azimuth of 30^o, 150^o, 210^o and 330^o.
- $\alpha 3$ represents the azimuth of 60^o, 120^o, 240^o and 300^o.
- $\alpha 4$ represents the azimuth of 90^o and 270^o.

Analysis of wellbore stability charts

As highlighted previously, the wellbore stability charts are plotted to determine the critical wellbore pressures that maintain stability at different well orientations in an NF stress regime. The same charts can be utilized to estimate the best wellbore trajectory to prevent sanding during production. For each studied depth, 64 charts are generated that gives a total number of 448 charts to cover all potential scenarios for Omani fields [29]. Overall, there are three common behaviors for the trend of the stability charts which are recognized and are summarized in Fig. 2.

Case 1

The stability chart in Fig. 3 is plotted with low rock cohesion where c = 500 psi. In this studied case, the critical wellbore pressure is equal to the initial formation pressure in all wellbore inclinations and azimuths. Therefore, rock failure represented by sand production will take place from day one of production in all wellbore inclinations and azimuths. In order to utilize this oil field, sanding control methods need to be selected properly and kept ready to handle the existing sanding challenge in the initial stage of production.

Table 2. Input parameters for cases (1, 2 and 3) at depth=5000 ft.

h **(Ft)**	σ_v **(psi/ft)**	σ_H **psi/ft)**	σ_h **(psi/ft)**	P_o **(psi)**	***C*** **(Psi)**	ϕ **(degree)**	ν	α_B
5000	1	0.85	0.8	2250	500, 1000, 2000	35	0.2	1

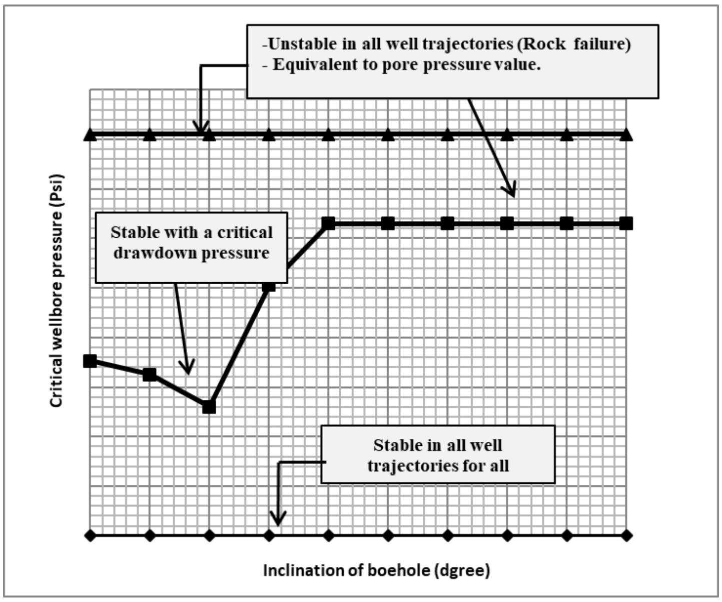

Fig. 2. Common behaviors of the sanding prediction charts

Case 2

In this case study, rock cohesion is equal to 1000 psi which makes the rock formation stronger than the first studied example. The stability chart corresponding to this scenario is shown in Fig. 4. In region B of the illustrated stability chart, the wellbore becomes unstable and sanding will take place. This will exactly happen when the well inclination is equal to 50° or more at any azimuth. In region A of the stability chart, where the well inclination is less than 50°, the critical wellbore pressure is reduced from the level of the pore pressure to lower values. From the developed stability chart, it is obvious that a well with an azimuth of 90° or 270° has lower critical wellbore pressure than other azimuths. In this case, the optimum well inclination is about 30°.

Adopting the suggested optimum well path or being close to it as possible will reduce the potential of sand production to the maximum. In addition, this case study shows that sanding potential is highly sensitive to the inclination and azimuth of the well that must have a geomechanical study.

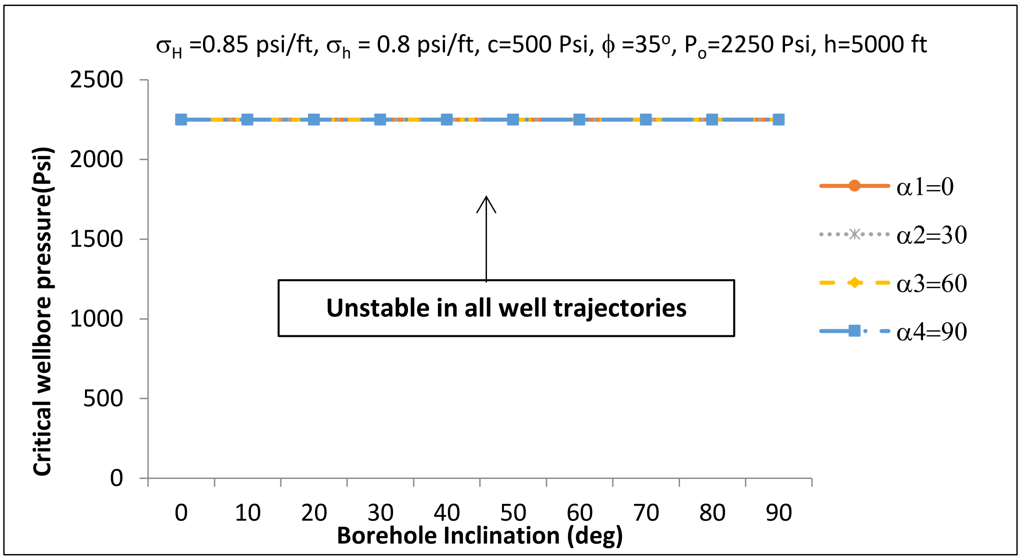

Fig. 3. Stability chart for case 1 which presents sanding from day one of production in all well trajectories

Case 3

Having a sandstone formation with a high cohesion equal to 2000 psi, as in this case, gives a higher strength for the rock compared to the previous two cases and the potential of sanding is minimized. In this example, the wellbore is fully stable in all wellbore trajectories and the sanding potential will not be encountered in at all over the well lifetime. This is indicated in the stability chart by getting a critical wellbore pressure equal to zero for all well paths as illustrated in Fig. 5.

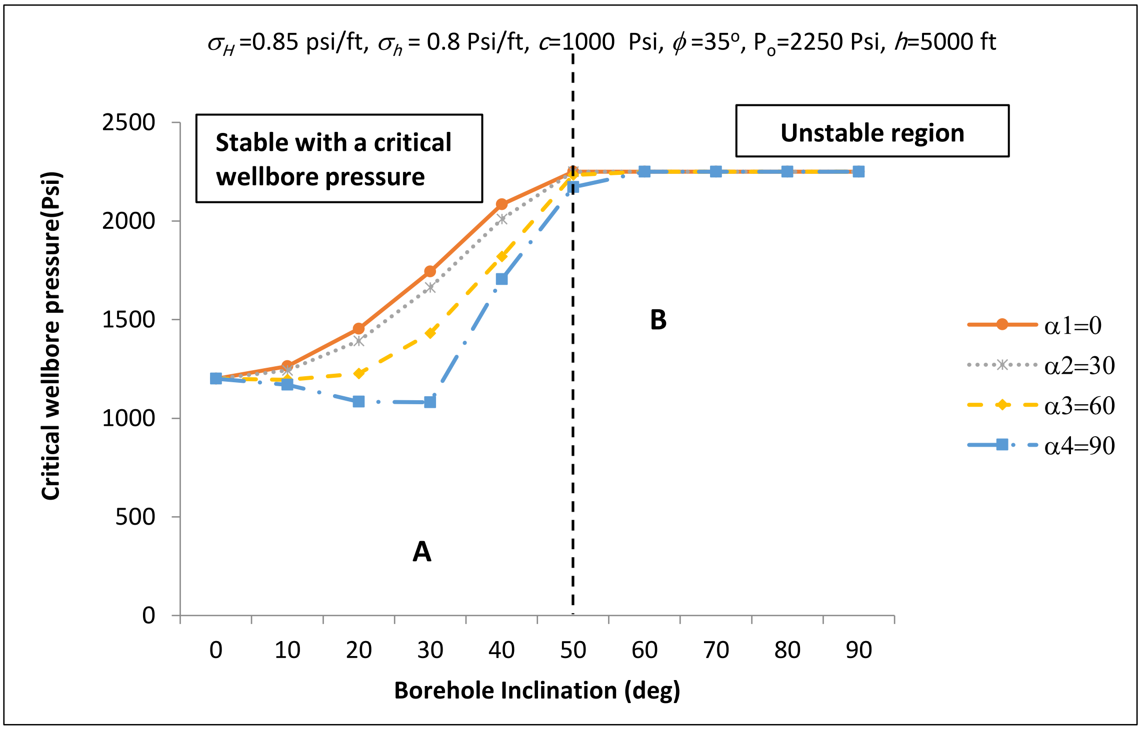

Fig. 4. Stability chart for case 2 with *c* =1000 psi which has a stable well path in region A.

With respect to the general optimum well path for Omani sandstone formation, it has been found from the generated charts that the optimum azimuth is always parallel to σ_h (i.e., $\alpha = 90°$). Moreover, the optimum well inclination is determined to have a range of 20° to 40° (see Table 3). Therefore, in order to minimize the potential of sand production in Omani oil fields, the wells should have inclinations of 30°±10° with a drilling direction parallel to the minimum horizontal *in situ* stress as possible. The determined optimum well trajectories are the same as those in drilling Omani shale formations [30]. These results support that the *in situ* stresses are the governing factors for wellbore trajectory optimization as reported by Al-Ajmi and Zimmerman [31]. Accordingly, for drilling and production in Omani oil fields, the common optimum stable well path is having an inclination of 30°±10° and azimuth parallel to σ_h in the field.

Table 3. The optimum well path from the wellbore stability charts [29].

Stress regime	σ_H (psi/ft)	σ_h (psi/ft)	$\gamma = i$ (deg)
NF	0.75	0.7	20
	0.8	0.7	30
	0.85	0.8	30
	0.9	0.8	40

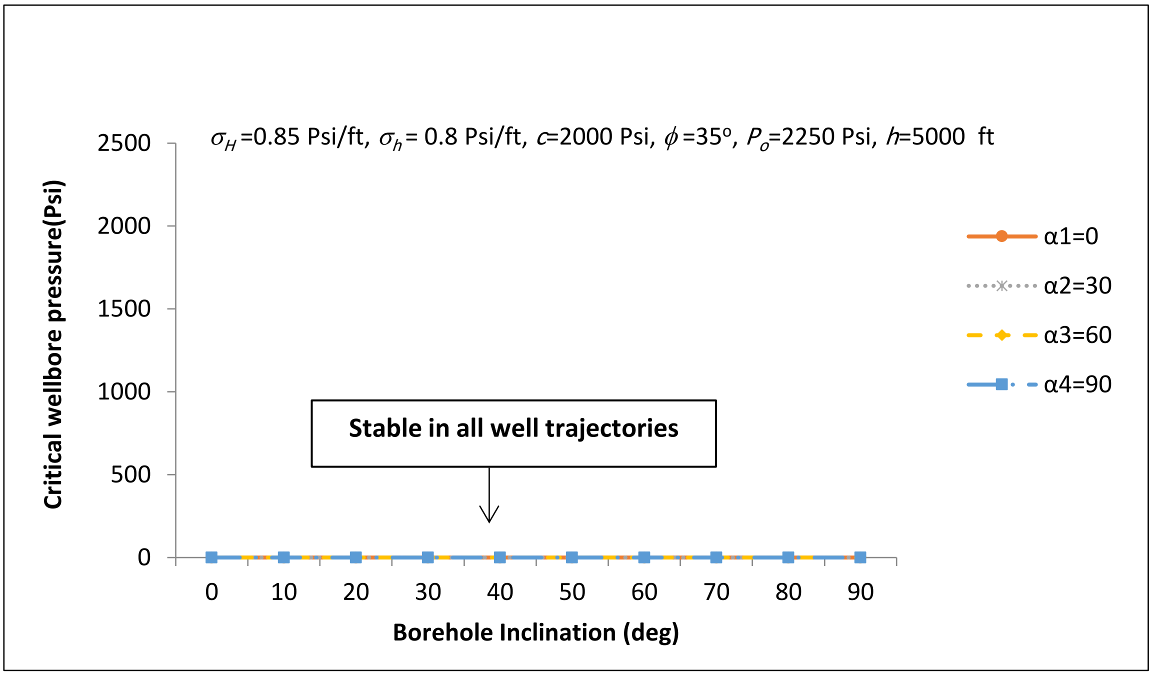

Fig. 5. Stability chart for case 3 with *c* =2000 psi which is fully stable in all well trajectories

Conclusions

The developed stability charts in this work made the complicated sand production prediction an easy task to adopt by petroleum engineers. Utilizing the stability charts, it has been observed that the optimum well trajectory for the production from sandstone formations in Oman is within an inclination of 30°±10° with a drilling direction parallel to the minimum horizontal *in situ* stress. Considering this information during the well design process will minimize the potential of sanding in the oil fields. The developed charts can be used for similar conditions in other countries, and, the conducted developing approach for the charts can be applied for other conditions worldwide to simplify the stability analysis.

Nomenclature

Symbol	Definition
ϕ	internal friction angle of the rock (degree)
C	cohesion of the material (psi)
A	Azimuth of the wellbore (degree)
I	inclination of the wellbore (degree)
P_o	gradients of pore pressure (psi)
α_B	Biot's coefficient
ν	Poisson's ratio
σ_H	major horizontal principal stress (psi/ft)
σ_h	minor horizontal principal stress (psi/ft)
σ_v	overburden stress (psi/ft)

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