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FULL LENGTH ARTICLE

Sand production prediction using ratio of shear modulus to bulk compressibility (case study)

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Abstract Sand production is a serious problem widely existing in oil/gas production. The problems resulting from sand influx include abrasion of downhole tubular/casing, subsurface safety valve and surface equipment; casing/tubing buckling, failure of casing or liners from removal of surrounding formation, compaction and erosion; and loss of production caused by sand bridging in tubing and/or flow lines. There are several methods for predicting sand production. The methods include use of production data, well logs, laboratory testing, acoustic, intrusive sand monitoring devices, and analogy. The methodologies are reviewed and the data needed for predicting sand production are enumerated. The technique used in this paper involves the calculation of shear modulus, bulk compressibility, and the ratio of shear modulus to bulk compressibility. The shear modulus to bulk compressibility ratio has been related empirically to sand influx. This Mechanical Properties Log method works 81% of the time. This technique is supported with examples and case studies from regions around the world known for sand production. The authors collected the information of the "Kaki and Bushgan Oilfield in Iran", set a sand production prediction to predict sand production potential. The technique has been successfully applied in reservoirs and results have been compared with testing data.

1. Introduction

Over 70% of world's oil and gas reserves are contained in sand formations where sand production is likely to become a problem during the life of the well [1]. Numerous solutions to halt sand production from oil and gas wells have been attempted, with various degrees of success. The most prevalent remedy is the gravel-pack completion, which blocks the influx of loose sand with specially selected gravel held in place by screens. This method is particularly expensive but not nearly as costly as losing a producer. Therefore, it is vital to know whether a well will produce sand before it is placed on production. The economic implications of sand problems are critical enough to require continuous improvement in sand-control techniques and sand production prediction methods. When developing a sandstone oil or gas reservoir, a prediction of sand production is required to evaluate the necessity of sand control [2].

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Nomenclature

C_b	Bulk compressibility	ΔP_p	Reservoir pressure depletion
CDP	Critical drawdown pressure	$\Delta\sigma_h$	Change in minimum horizontal stresses
DST	Drill stem test	$\Delta\sigma_H$	Change in maximum horizontal stresses
E	Young's modulus	σ_H	Horizontal maximum stress (Intermediate stress)
G	Shear modulus	σ_h	Horizontal minimum stress (Minimum stress)
TWC	Thick-walled cylinder	σ_v	Vertical overburden stress (Maximum stress)
UCS	Unconfined Compressive Strength	υ	Poisson's ratio

2. Sand production

The classification of field measurements of sand production is considered an essential part of sand prediction. A classification is developed, based on field observations, to allow for a better comparison and interpretation of sand production events.

2.1. Types of sand production

2.1.1. Transient sand production

Transient sand production refers to a sand concentration declining with time under constant well production conditions. This phenomenon is frequently observed during clean-up after perforating or acidizing, after bean-up [3] and after water breakthrough. Fig. 1, shows field example with a sand volume 1 L and decline period [4].

2.1.2. Continuous sand production

In a great number of fields, continuous levels of sand production are observed [3]. Part of the continuously produced sand settles inside the wellbore and increases the hold-up depth. Depending on the lifting capacity of the fluid flow and the sand concentration (part of) the (perforated) producing interval may eventually be blocked [4].

2.1.3. Catastrophic sand production

Catastrophic sand production refers to events where a high rate sand influx causes the well to suddenly choke and/or die. Two catastrophic failure scenarios can be imagined. The first one corresponds to slugs of sand creating sand bridges of moderate volume in tubing or choke, e.g. during or after bean-up and shut-in operations. The second one refers to a massive influx of sand, filling and obstructing the wellbore [4].

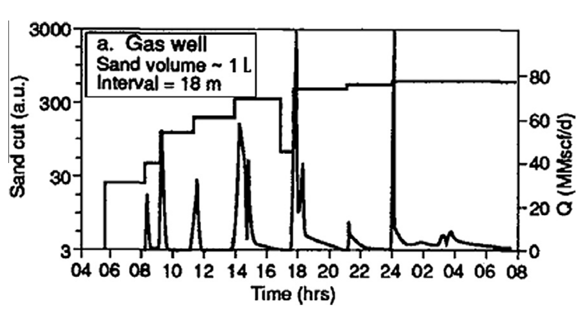

Figure 1 Transient sand production with a sand volume 1 L and decline period [4].

2.1.4. Sand production mechanisms

Mechanisms causing sand production are related to the following: formation strength, flow stability, viscous drag forces, and pressure drop in the wellbore. Operators cope with sand production in many ways. One way of accomplishing this goal is to limit production rates to levels that avoid sand production. In some cases this is the most cost effective method of sand control, but in many cases low production rates are uneconomical. Several factors lead to sand production. The most critical factors are: (1) formation strength; (2) in-situ stress; and (3) production rate [1].

2.1.5. Formation strength

The hydrocarbon production process is associated with reservoir depletion which results in a decrease of reservoir pore pressure. Consequently, the effective overburden pressure defined as total overburden pressure minus pore pressure, increases. Formation collapse is most likely if the effective stress exceeds the formation strength.

2.1.6. Changing in-situ stresses

Generally, the in-situ stresses can be estimated. The horizontal minimum stress (σ_h) can be measured from formation integrity test (leak-off) and the overburden stress (σ_v) from overburden density data. In a relatively relaxed geologic region such as a young deltaic sedimentary basin, the minimum and intermediate stresses tend to be approximately equal. However, in general, the intermediate stress (σ_H) is about 10% more than the minimum stress [5].

During the life of an oil field, in-situ stresses in the reservoir will change as the reservoir pressure depletes. Assuming no lateral strain on the border of the reservoir during depletion, Eq. (1) can be used to evaluate the change in the in-situ stresses.

$$\Delta\sigma_H = \Delta\sigma_h = \alpha\frac{1-2\upsilon}{1-\upsilon}\Delta P_p \tag{1}$$

where and are the change in maximum and minimum horizontal stresses only, is reservoir pressure depletion, is Poisson's Ratio, and α is Biot's poroelastic constant [6].

2.1.7. Production rate

An increase in the production rate leads to a large fluid pressure gradient near the wellbore, and tends to draw sand into the wellbore. The mechanism that causes a consolidated sand to fail is believed to result from a combination of pressure and fluid flow. Because these mechanisms are closely tied to each other, determining actual mechanism may be a moot point [7].

3. Sand control

In terms of sand control, there are two main classes of techniques available; sand prevention by passive method and sand control using mechanical exclusion (gravel-packing) or screen less completion (sand stabilization by chemical consolidation or sand lock). Sand prevention by passive method covers techniques to minimize or eliminate sand production to manageable levels. The techniques include perforation techniques and maximum sand-free drawdown rate [1].

4. Sand production prediction

4.1. Literature review

The history of predictive models for sand control is relatively short. Stan and Hilchie [8], who introduced the first significant technique, related the formation's shear strength to the well's sand production. Data from sonic and density logs were used to relate production of a sand-producing well to that of a well under study. The limitations of the method are that (1) a well must be completed and tested until it produces large quantities of sand before reliable results are obtained, (2) the problems of pressure depletion and water production were not addressed, (3) the well is investigated at one point in time without any method of extrapolating into the future, and (4) completions are assumed to be in clean sands without skin effects. Tixier et al. [9] reported the development of the mechanical properties log, which was basically a log-derived model. Their empirical correlation implied that a threshold for sanding existed at $G/C_b = 0.8 \times 10^{12}\,\text{psi}^2$ where G is shear modulus and C_b is bulk compressibility. This correlation can state only whether sanding will be a problem at current conditions and have shortcomings similar to those of Stan and Hilchie's model. A major drawback is the lack of quantitative information. The method states whether a well will be a sand producer, but a maxi mum sand-free rate cannot be calculated from the given ratio of G/C_b [10].

The "sand strength" log [11] was developed in 1981. This model, unlike the previous two, relates sand production to the stress levels existing around the near-wellbore reservoir rock. Mohr's circle stress analysis technique is the heart of the method. Log-derived elastic rock properties are used to obtain compressibility constants and in-situ values of stress around the borehole. This method has been gaining acceptance in the industry as a reliable predictor of sand production in hydrocarbon producers [12] that do not produce significant water volumes.

A study of Kaki Oilfield wells concluded that Mohr's failure analysis technique with a 200-psi [1378-MPa] safety factor would have been a viable method for making sand-control decisions. Although Mohr's stress analysis technique, referred to here as the dry model, is good when applied to wells with no water production, its limitations were quickly realized. Although the experience to date has been predominantly with gas and oil production, it is believed that production with a high water cut may require higher intrinsic shear strength [9].

Weissenburger et al. [13] also realized the need for a system to predict sand production. An engineering system provided an iterative pathway to integrate rock mechanics, geology, logging; and reservoir-management information. Morita et al. [14,15] provided a numerical model and a parametric study of sand-production prediction without the effect of water production.

4.2. Sand prediction technique

There are several factors that lead to sand production. The factors believed to influence sand production are presented in Table 1. Various approaches to sand prediction use different critical factors. Due to the practical difficulties of monitoring and recording several, only a small selection of these factors is used. Notable methods of predicting sand production are classified in Table 2.

4.3. Field observation

Sand prediction techniques based on field experience rely on establishing a correlation between sand production well data and field and operational parameters. The technique most frequently used for prediction of sand production is analogy with other wells in the same horizon, field, or area.

Table 1 Parameter influencing sand production [4].

Formation	Rock	Strength Vertical and horizontal in-situ stresses (change during depletion) Depth (influences strength, stresses and pressures)
	Reservoir	Far field pore pressure (changes during depletion) Permeability Fluid composition (gas, oil, water) Drainage radius Reservoir thickness Heterogeneity
Completion	Wellbore orientation, wellbore diameter Completion type (open hole/perforated) Perforation policy (height, size, density, phasing, under/overbalance) Sand control (screen, gravel pack, chemical consolidation) Completion fluids, stimulation (acid volume, acid type) Size of tubular	
Production	Flow rate Drawdown pressure Flow velocity Damage (skin) Bean-up/shut-in policy Artificial lift technique Depletion Cumulative sand volume Water/gas coning	

Table 2 Classification of sand prediction methods.

1. Field observation	Correlations	One-parameter correlations Two-parameter correlations Multi parameter correlations
	Analogy method	Production rate method
2. Laboratory experiments	Thick wall cylinder (TWC) test Static rock elastic properties	
3. Use of well log data	Mechanical properties log	
4. Theoretical modeling	Analytical	Cavities Compressive failure Cavities tensile failure Cavities erosion
	Numerical Integrated engineering system	

4.4. Laboratory experiments

Laboratory sand production experiments are carried out to observe and simulate sand production in a controlled environment. The laboratory tests require substantial time particularly in offshore and inland water locations. Theoretical sand prediction models can be validated against the laboratory observations. A simplified model test using a thick-walled cylinder sample has been developed for field application based on sand production tests carried out on hollow cylinder samples [16,17].

4.5. Use of well log data

This involves the computer calculation of shear modulus, bulk modulus, bulk compressibility, and the ratio of shear modulus to bulk compressibility from resistivity, neutron, acoustic, and density log data. The result of this computation is called Mechanical Properties log [18,9].

4.6. Theoretical modeling

The theoretical sand prediction tools require a mathematical formulation of the sand failure mechanism. The mechanisms currently held responsible for sand production are compressive failure [19], tensile failure [19] and erosion [18].

5. Case studies

The shear modulus to bulk compressibility ratio has been related empirically to sand influx. This empirical correlation implied that a threshold for sanding existed at $G/C_b = 0.8 \times 10^{12}\,\text{psi}^2$ $[5.516 \times 10^{15}\,\text{pa}^2]$ where G is shear modulus and C_b is bulk compressibility, whereas values less than $0.7 \times 10^{12}\,\text{psi}^2$ suggest a high probability of sanding. The method states whether a well will be a sand producer, but a maxi mum sand-free rate cannot be calculated from the given ratio of G/C_b [3]. In the following case studies, three field data are used to verify this existing empirical correlation.

5.1. Case 1 – Bushgan oilfield in Iran

Bushgan oilfield is located in Iran. In DST (drill stem test) operations of exploration wells W12-1-2&3, some formation sands were detected, due to test pressure drop change in each DST operations being too large; it is difficult to get accurate critical drawn down pressure. Based on conventional rock analysis reports, there is little potential sanding for this oilfield, but it is true that it is sanding in DST operation. The uncertainty of sanding makes well completion plan unclear.

Most of the G/C_b of wells W12-1-2&3 are larger than $2.1 \times 10^{12}\,\text{psi}^2$, much more $0.8 \times 10^{12}\,\text{psi}^2$ which is used as limit line for no sanding judgment. According to G/C_b values calculated from logging data, the wells of the oilfield are of less potential sanding in initial production phase. Whereas using UCS perdition method, the CDP of pay-zone is achievable. See Tables 3 and 4.

The results of G/C_b show that most of pay zone are less of potential to sanding, although the well will produce sand when production drawdown pressures exceed CDP predicted by UCS method [20].

5.2. Case 2 – An oil field offshore south of Iran

This case study field is situated in offshore Iran. Over a period of more than 20 years of field production life, the reservoir pressure has depleted by approximately 1000 psi, production is declining and a further reduction in reservoir pressure of 700 psi is predicted. Rock mechanical testing was conducted on reservoir core materials obtained from four depth intervals in one of the existing wells (Well 1, termed reference well). The derived elastic parameters for all the samples are summarized in Table 5. The shear modulus (G) and bulk compressibility (C_b) were determined from the modulus of elasticity (E) and Poisson's ratio using Eqs. (2) and (3) [21].

$$G = \frac{E}{2(1+\upsilon)} \tag{2}$$

$$C_b = \frac{3(1-2\upsilon)}{E} \tag{3}$$

Table 3 CDP of well W12-1-2 for Bushgan oilfield in Iran.

DST section	Average CDP, (psi)
DST 1	3292
DST 2	4119
DST 3	2190
DST 4	3016
DST 5	2103

Table 4 CDP of well W12-1-3 Bushgan oilfield in Iran.

DST section	Average CDP, (psi)
DST 1	2393
DST 2	1856
DST 3	1943
DST 4	2625
DST 5	2204

Table 5 Summary of elastic parameters of cores Well 1 – an oil field offshore South Iran.

Sample	E (10^6 psi)	ϑ
1	1.208601	0.31
2	1.069219	0.22
3	1.058196	0.3
4	0.295442	0.32
5	0.28645	0.3
6	0.186374	0.41
7	0.453679	0.28
8	0.502556	0.27
9	0.883716	0.32
10	0.416694	0.26
11	0.36361	0.19
12	0.36419	0.17
13	1.208601	0.31
14	1.069219	0.22
15	1.058196	0.3
16	0.295442	0.32

Table 6 Summary of calculated static constants Well 1 – an oil field offshore South Iran.

Sample	E (10^6 psi)	ϑ	G (10^6 psi)	C_b (10^{-6} psi^{-1})	G/C_b (10^{12} psi^2)
1	1.208601	0.31	0.461298	0.94323953	0.489057106
2	1.069219	0.22	0.438205	1.571239826	0.278890999
3	1.058196	0.3	0.406999	1.134004934	0.358903761
4	0.295442	0.32	0.11191	3.655537555	0.030613806
5	0.28645	0.3	0.110173	4.18921519	0.026299201
6	0.186374	0.41	0.06609	2.897404669	0.022810055
7	0.453679	0.28	0.177218	2.909549233	0.060909151
8	0.502556	0.27	0.197857	2.745961039	0.072053757
9	0.883716	0.32	0.334741	1.22211226	0.273903528
10	0.416694	0.26	0.165355	3.455774452	0.047848813
11	0.36361	0.19	0.152777	5.115370961	0.02986632
12	0.36419	0.17	0.155637	5.43672043	0.028626967
13	1.208601	0.31	0.461298	0.94323953	0.489057106
14	1.069219	0.22	0.438205	1.571239826	0.278890999
15	1.058196	0.3	0.406999	1.134004934	0.358903761
16	0.295442	0.32	0.11191	3.655537555	0.030613806

Table 6 shows the Calculated Static Constants constructed based on the data in the reference well. All of the G/C_b of samples are smaller than 0.5×10^{12} psi^2, much less 0.7×10^{12} psi^2 which is used as limit line for sanding. According G/C_b values calculated from logging data, the wells of the oilfield are of high potential sanding. Compare the sanding evaluation result with the field sanding experience; consistent with field observation.

Table 7 Summary of data and calculated elastic constant – Kaki wells producing free water.

Well	G (10^6 psi)	C_b (10^{-6} psi^{-1})	G/C_b (10^{12} psi^2)
3	1.29	0.731	1.764706
4	1.31	0.718	1.824513
5	1.43	0.674	2.121662
6	1.12	0.819	1.367521
7	1.21	0.773	1.56533
10	1.67	0.617	2.706645
13	1.59	0.636	2.5
15	1.85	0.559	3.309481
17	1.22	0.763	1.598952
18	1.52	0.713	2.131837
19	1.55	0.655	2.366412
20	1.6	0.66	2.424242
23	1.37	0.682	2.008798
24	1.85	0.559	3.309481

Table 8 Summary of well test data – Kaki wells producing free water.

Well	Drawdown (psi)	Water production (bpd)	Sand	G/C_b (10^{12} psi^2)
10	753	16	No	2.706645
	1098	19	No	
	494	34	No	
	307	45	Trace	
	448	53	Yes	
15	380	2	No	3.309481
	178	67	Yes	
17	50	0	No	1.598952
	50	353	Yes	
18	1379	3	Yes	2.131837
	50	0	No	
	50	128	Yes	
19	540	0	No	2.366412
	50	527	Yes	
21	143	0	No	Not available
	515	214	Yes	

Based on the results of the study it can be concluded that sand production risk is very high, and downhole sand control would be needed. Openhole completion with sand control screen was adopted in the infill drilling program [21].

5.3. Case 3 – Kaki wells producing free water

A study was undertaken to develop a model capable of predicting the sanding of Kaki wells that also produce free water. Field data from gas wells and log-derived properties of reservoir rock were used to construct a usable model. The well tests all have water production exceeding 3 bbl water/MMscf gas. Shear modulus, bulk compressibility data for these wells and the computed shear modulus [22] to bulk compressibility ratio are tabulated in Table 7.

Although the amount of G/C_b implied that there is no sand production, it is observed that production with high water cut will cause sand production [22]. These tests reveal the inability of the G/C_b ratio method to predict sand production when free-water pro duction is present [23]. Obviously, a better prediction method is needed. Considering summary of well test data in Table 8, it can easily be understood that occurrence of water leads to sanding at lower drawdown than when water was absent.

6. Conclusion

(1) Sand production types and sand production mechanisms have been classified.
(2) Conventional sand prediction techniques have been reviewed.
(3) G/C_b ratio correlation of sand prediction has been verified by three field data. Based on the analysis performed in field case studies, the following conclusions are arrived with:
  - In normal condition, there is good relation among G/C_b ratio and sand production.
  - Even though the result of G/C_b shows that formations have no potential to sanding, they will produce sand when production drawdown exceeds critical drawdown pressure which is predicted by UCS method.
  - Although the amount of G/C_b implied that there is no sand production, it is observed that production with high water cut will cause sand production. Therefore it can be concluded that production with a high water cut requires higher threshold value for G/C_b ratio (greater than 0.8×10^{12} psi^2).

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