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## An analytical model to predict the volume of sand during drilling and production

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### ABSTRACT

Sand production is an undesired phenomenon occurring in unconsolidated formations due to shear failure and hydrodynamic forces. There have been many approaches developed to predict sand production and prevent it by changing drilling or production strategies. However, assumptions involved in these approaches have limited their applications to very specific scenarios. In this paper, an elliptical model based on the borehole shape is presented to predict the volume of sand produced during the drilling and depletion stages of oil and gas reservoirs. A shape factor parameter is introduced to estimate the changes in the geometry of the borehole as a result of shear failure. A carbonate reservoir from the south of Iran with a solid production history is used to show the application of the developed methodology. Deriving mathematical equations for determination of the shape factor based on different failure criteria indicate that the effect of the intermediate principal stress should be taken into account to achieve an accurate result. However, it should be noticed that the methodology presented can only be used when geomechanical parameters are accurately estimated prior to the production stage when using wells and field data.

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## 1. Introduction

Up to 70% of oil and gas reservoirs worldwide are located in poorly consolidated formations (Nouri et al., 2003, 2007). In these reservoirs, when the pressure is depleted to a point where the maximum tangential stress exceeds the formation's strength, the formation fails and sand production is triggered. The sand production phenomenon is generally taking place through three stages: (1) loss of mechanical integrity of rocks surrounding the borehole, (2) separation of solid particles due to the hydrodynamic force, and (3) transportation of the particles to the surface by production. This phenomenon is particularly important when significant changes of in-situ stresses, high production rates, and collapses of cavities are observed (Wang and Dusseault, 1991; Kooijman et al., 1996; Abass et al., 2002). Solid production in non-granular rocks such as carbonates shares the same concept and

is triggered when excessively broken rocks due to natural fractures are transported by production fluids (Papamichos and Furui, 2013).

Excessive sanding or solid production may damage the downhole and surface equipment, induce wellbore instability, and cause difficulties during completion and production phases. Sand production has, therefore, remained as an ongoing challenge in the reservoir management and field operations. A better understanding of the sanding mechanism should allow for prediction of the initiation of sanding more realistically. This is, however, a complex mechanism as sanding is impacted by various parameters, including geological, geomechanical and fluid characteristics of the formations as well as the initial state of stresses, pressure conditions, wellbore completions and boundary conditions (Papamichos and Malmanger, 1999; Vaziri et al., 2000; Palmer et al., 2000; van den Hoek et al., 2000). Considering the impact of these parameters in a simple model is not practical and assumptions are required to derive models for prediction of sanding. One of these assumptions is the one where shear failure is considered as the most likely mechanism in unconsolidated formations, causing sand/solid production to take place in the presence of the fluid flow (Wang and Papamichos, 2012).

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There have been many sand production risk assessments performed using geomechanical models where analytical approaches were proposed to predict either the initiation of sanding or the extent of rock failure around the borehole. For example, Bratli and Risnes (1981) and Risnes et al. (1982) developed analytical solutions for rock failure around the boreholes which was only suitable for a steady state flow condition. Bratli and Risnes (1981) introduced a cohesive failure model and calculated a critical bottomhole pressure for sanding in a uniformly stressed cylindrical borehole. Their model, however, could not be used for the prediction of sanding due to shear failure, which is more common than cohesive failure in unconsolidated formations. Morita et al. (1989) proposed the so-called equivalent plastic strain (EPS) criterion and stated that sanding occurs once a critical plastic strain is achieved. Their approach could not be validated completely later when it was used for a gas field (Wang and Dusseault, 1991). McLellan and Wang (1994) developed an analytical approach to evaluate the failure of boreholes by assuming an exclusive elastic–brittle–plastic strain-softening behavior for the formations. Weingarten and Perkins (1995) developed a model to predict the sanding exclusively for the perforations made in loose formations based on the assumption of elastic–perfectly plastic materials, where the effect of the steady-state and compressible fluid flow was taken into account. Bradford et al. (1998) proposed analytical models for predicting the failure around the boreholes under an isotropic in-situ stress condition which could not be used for a tectonically active region with three independent principal stresses. Ewy et al. (2001) proposed a Lade model to enhance the accuracy of predictions previously provided by the Mohr–Coulomb criterion and/or Drucker–Prager criterion. Their model, however, did not find a wide application due to the limitation and complexity of the Lade equation. Vaziri et al. (2002) used different sand production criteria for predictions in a high temperature and high pressure well and indicated a high level of conservatism in the predictions provided. Nouri et al. (2006) developed a new set of criteria for prediction of sanding using the conservative Mohr–Coulomb failure criterion through experimental and numerical analyses. Osisanya (2010) developed an approach based on the production, well logs and laboratory data to determine the initiation of sanding, but did not indicate the importance of predicting the volume of sand if it is initiated. Wang and Papamichos (2012) compared the shear, cohesive and effective plastic strain sanding criteria by doing calibration with the results obtained from a perforated test in sandstone. They suggested the plastic strain approach as the best method for the prediction of sanding, although the accuracy of results was questionable. Lamorde et al. (2014) developed an approach to determine the volume of sand produced based on the yield zone and fracture energy dissipation around the wellbore. However, their approach requires very complicated calculations and experimental studies to determine the energy dissipation.

The aim of this paper is to present a new methodology based on changes in the geometry of boreholes for predicting the volume of sand produced during drilling and depletion phases. The application of this approach will be initially at the reservoir assessment stage, where the risk of sand production must be quantified to develop a management strategy or to satisfy regulatory authorities.

## 2. Sand prediction models

Predicting the onset of sanding is a long standing geomechanical issue which has been the subject of many studies such as those presented earlier in the Introduction section. According to these studies, approaches developed to predict sand production can be divided into three main categories of empirical correlations, analytical models and numerical analysis.

Through the use of empirical correlations, the relationships between the onset of sanding and effective parameters, causing the sanding to take place, are established (Veeken et al., 1991). These correlations are, however, developed based on particular field data and their results may not be generalized to any other fields.

Analytical models are used to predict the sanding when critical conditions for the initiation of sanding are determined by the analysis of the stress state near the wellbore or perforations (Cerasi et al., 2005; Detournay et al., 2006). Simplifying the geometry of the problem and rock's mechanical properties, analytical equations are used to estimate the onset of sanding. These models are easy to be used and widely acceptable for the sand production evaluation (Addis et al., 2008). Although analytical models suffer from limitations due to simplified assumptions, they are still commonly used in complex well geometries and subsurface environments.

Numerical models are perhaps the best approach for the analysis of a combination of effective parameters contributing to the onset of sanding. Finite element (Watson and Jones, 2009) and finite difference (Detournay et al., 2006; Nouri et al., 2007) numerical models have been used to assess the variation of the stress state when the fluid flow is presented. They can be used for the quantitative evaluation of the sand volume, but require a large data acquisition.

In this section, a new analytical solution for determination of the volume of sand produced during drilling and production is presented based on the changes in the shape of the borehole. The approach can be used in conjunction with different failure criteria to estimate the sanding onset in the presence of formation strengths and principal stresses.

### 2.1. A new elliptical model for prediction of sanding

Boreholes are expected to have a circular shape, but in practice, due to stress concentrations around the borehole, the borehole tends to change its geometry to reach a new state of stability. Generally speaking, the optimal shape (i.e. circular shape) of the borehole changes during the life of a well and may become elliptical due to shear failure. This concept is depicted in Fig. 1.

One of the approaches conventionally used for determination of the maximum and minimum tangential stresses in the elliptical

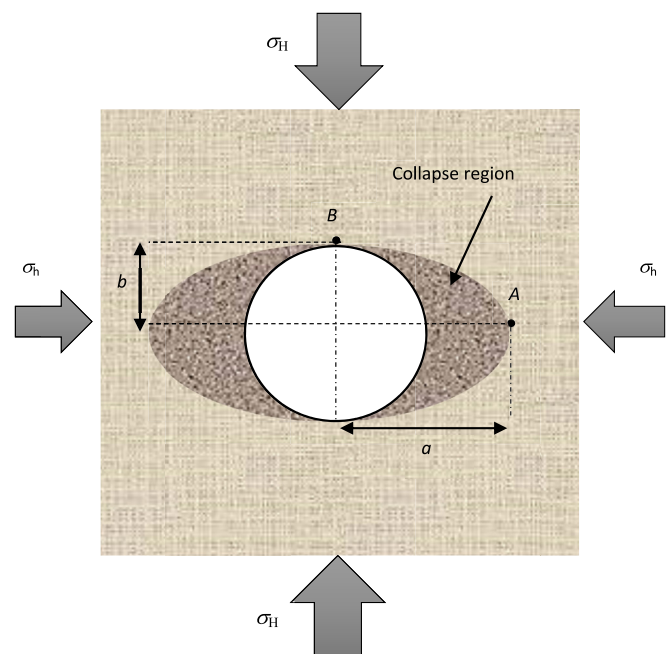


Fig. 1. Changes in the shape of the borehole as a result of shear failure.

borehole is developed by Lekhnitskii (1968) and formulated as follows:

$$\sigma_A = (1 + 2c)\sigma_H - \sigma_h - \left(\frac{2}{c} - 1\right)P_w \tag{1}$$

$$\sigma_B = \left(1 + \frac{2}{c}\right)\sigma_h - \sigma_H - (2c - 1)P_w \tag{2}$$

where  $\sigma_A$  and  $\sigma_B$  are the tangential stresses at points A and B around the wellbore, respectively, as shown in Fig. 1;  $\sigma_H$  and  $\sigma_h$  are the maximum and minimum horizontal stresses, respectively;  $P_w$  is the wellbore pressure and the parameter  $c$  is a function of borehole diameters (i.e.  $a$  and  $b$  in Fig. 1) which is defined as

$$c = \frac{-\left(\sigma_H - \sigma_h + P_w - \frac{1+\sin\phi}{1-\sin\phi}P_w - 2S_0\frac{\cos\phi}{1-\sin\phi}\right) + \sqrt{\left(\sigma_H - \sigma_h + P_w - \frac{1+\sin\phi}{1-\sin\phi}P_w - 2S_0\frac{\cos\phi}{1-\sin\phi}\right)^2 + 16\sigma_H P_w}}{4\sigma_H} \tag{8}$$

$$c = b/a \tag{3}$$

Borehole collapse is induced when the mud weight used for drilling is not able to apply enough pressure to resist against the extreme formation pressure. This kind of failure is often leaving an elliptical borehole shape behind. In the next section, a methodology based on the elliptical borehole shape is proposed using three well-known failure criteria to estimate the volume of sand.

2.1.1. Mohr–Coulomb criterion

Mohr–Coulomb shear failure criterion is one of the most commonly used and well-known criteria in many engineering applications. This criterion is expressed as

$$c = \frac{-\left(\sigma_H - \sigma_h + P_w - 2S_0\frac{\cos\phi}{1-\sin\phi}\right) + \sqrt{\left(\sigma_H - \sigma_h + P_w - 2S_0\frac{\cos\phi}{1-\sin\phi}\right)^2 + 16\sigma_H P_w}}{4\sigma_H} \tag{10}$$

$$\tau = S_0 + \mu\sigma_n \tag{4}$$

where  $\sigma_n$  and  $\tau$  are, respectively, the normal and shear stresses;  $S_0$  is the cohesion and  $\mu$  is the coefficient of internal friction.

The linearized form of the criterion is written in the principal stress space:

$$\sigma_1 = \sigma_c + q\sigma_3 \tag{5}$$

where

$$q = \left[ (\mu^2 + 1)^{\frac{1}{2}} + \mu \right]^2 = \tan^2\left(\frac{\pi}{4} + \frac{\phi}{2}\right) \tag{6}$$

where  $\sigma_1$  is the major principal stress at failure,  $\sigma_3$  is the minor principal stress at failure,  $\sigma_c$  is the uniaxial compressive strength (UCS) and  $\phi$  is the internal friction angle.

Shear failure during drilling occurs once the maximum induced tangential stress at point A, as shown in Fig. 1 (i.e.  $\sigma_A$ ), is higher than the radial stress ( $\sigma_r = P_w$ ). Thus, in the worst case scenario, the tangential stress is the maximum and the radial stress is the minimum principal stresses around the borehole. As a result, Eq. (1) can be substituted into Eq. (5) to give

$$(1 + 2c)\sigma_H - \sigma_h - \left(\frac{2}{c} - 1\right)P_w = \sigma_c + qP_w \tag{7}$$

Eq. (7) can then be rearranged to determine the parameter  $c$  as

At the initial stage of production, the pore pressure at the borehole wall becomes equal to the wellbore pressure and, as a result, the effective radial stress becomes zero ( $\sigma_r = P_w - P_p = 0$ , where  $P_p$  is the pore pressure). Considering the tangential stress ( $\sigma_A$ ) as the maximum principal stress and the radial stress ( $\sigma_r$ ) as the minimum principal stress for shear failure, Eq. (5) can be rewritten as

$$(1 + 2c)\sigma_H - \sigma_h - \left(\frac{2}{c} - 1\right)P_w = \sigma_c \tag{9}$$

As a result, the parameter  $c$  for the production stage can be obtained as a function of the in-situ stress, wellbore pressure, friction angle and cohesion by rearranging Eq. (9) as

It should be noticed that Eq. (10) can only be used for the prediction of sanding when updated effective stresses are recalculated based on the changes in the magnitude of the pore pressure due to depletion. Two equations were, therefore, presented at the end of this section to estimate the changes in the magnitude of effective stresses as depletion progresses. Having the parameter  $c$  determined during drilling (i.e. Eq. (8)) and production (i.e. Eq. (10)), the volume of sand produced can be calculated using the equation formulated below:

$$V = \frac{\pi}{4}ab - \frac{\pi}{4}b^2 = \frac{\pi}{4}\frac{1-c}{c}b^2 \tag{11}$$

where  $V$  is the rate of sand production per unit length of the wellbore ( $m^3/m$ ).

2.1.2. Hoek–Brown criterion

Hoek–Brown failure criterion was originally developed in the early 1980s and undergone numerous revisions (Hoek and Brown, 1980, 1997; Hoek et al., 1995, 2002). It uses two dimensionless parameters,  $m$  and  $s$ , which depend mainly on the rock type and degree of heterogeneity, for estimation of the ultimate strength of rocks. According to this criterion, the relationship between the maximum and minimum stresses is expressed as

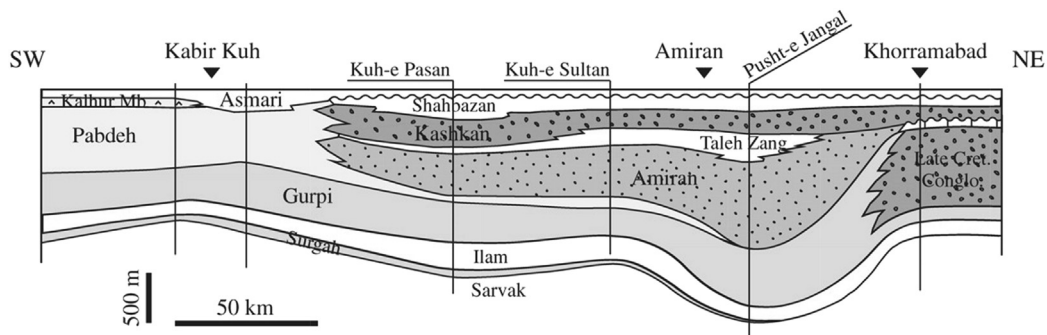
$$\sigma_1 = \sigma_3 + \sigma_c \left( m \frac{\sigma_3}{\sigma_c} + 1 \right)^{\frac{1}{2}} \quad (12)$$

Assuming the same situation as before for a drilling practice, where the tangential stress ( $\sigma_A$ ) is the maximum principal stress and the radial stress ( $\sigma_r = P_w$ ) is the minimum principal stress, Eq. (1) can be substituted into Eq. (12) to give

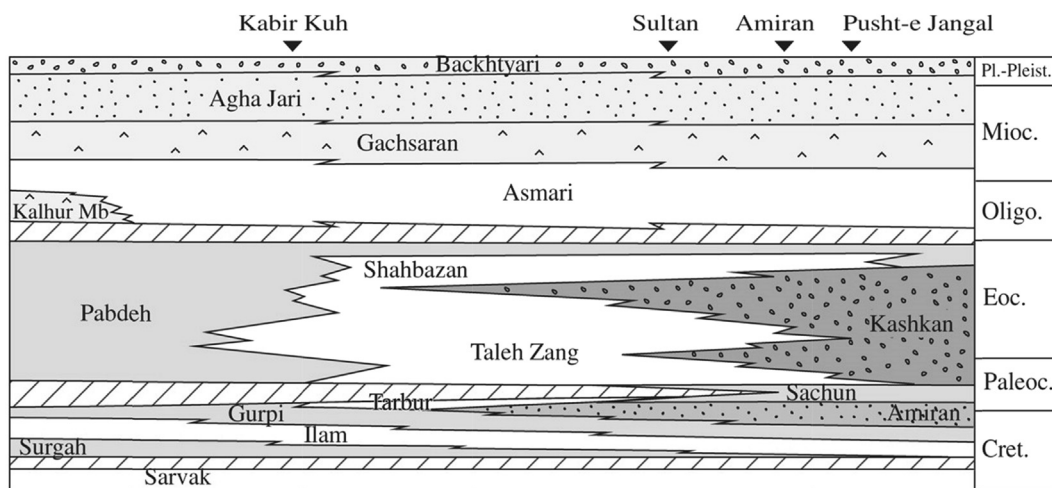
$$(1 + 2c)\sigma_H - \sigma_h - \left( \frac{2}{c} - 1 \right) P_w = P_w + \sigma_c \left( m \frac{P_w}{\sigma_c} + 1 \right)^{\frac{1}{2}} \quad (13)$$

Eq. (13) can then be rearranged to derive the parameter  $c$  as

$$c = \frac{- \left[ \sigma_H - \sigma_h + P_w - \sigma_c - \sigma_c \left( m \frac{\sigma_3}{\sigma_c} + 1 \right)^{\frac{1}{2}} \right] + \sqrt{\left[ \sigma_H - \sigma_h + P_w - \sigma_c - \sigma_c \left( m \frac{\sigma_3}{\sigma_c} + 1 \right)^{\frac{1}{2}} \right]^2 + 16\sigma_H P_w}}{4\sigma_H} \quad (14)$$



A. Modified from James and Wynd (1965)



B. Modified from Alavi (2004)

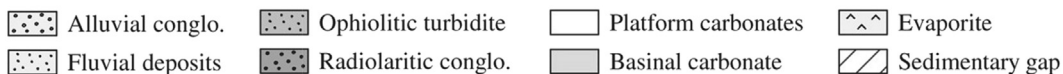


Fig. 2. Geological stratigraphy of the field (from Homke et al., 2009).

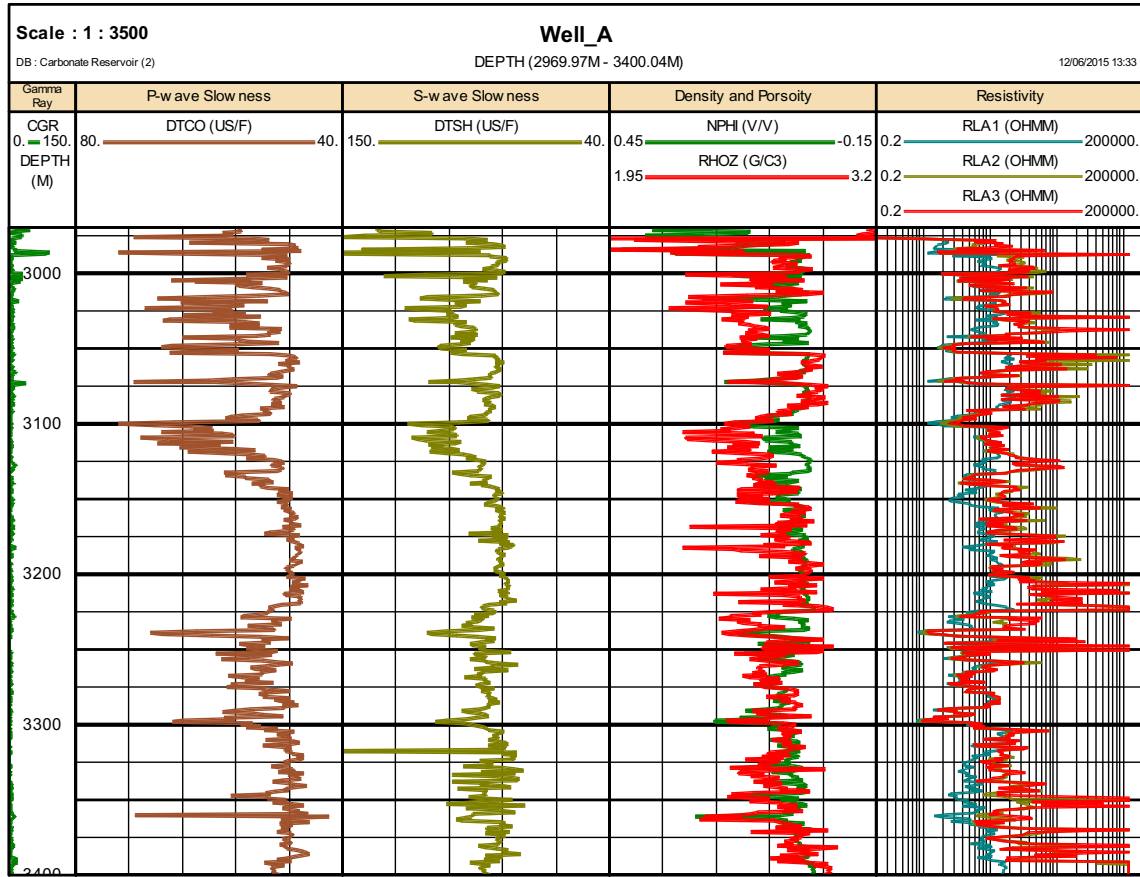


Fig. 3. Log data of Well A used for the purpose of this study.

Considering the initial stage of depletion, where the pore pressure is equal to the wellbore pressure ( $\sigma_r = 0$ ) and the tangential stress ( $\sigma_A$ ) is obtained using Eq. (1), Eq. (12) changes to

$$(1 + 2c)\sigma_H - \sigma_h - \left(\frac{2}{c} - 1\right)P_w = \sigma_c \quad (15)$$

This is a same equation as Eq. (7), but the UCS in the Hoek–Brown criterion cannot be simply related to the cohesion and friction angle of the rock. The parameters,  $m$  and  $s$ , in the Hoek–Brown criterion, however, can be linked to the cohesion and friction angle parameters of the Mohr–Coulomb criterion using the approach presented by Lee and Bobet (2014). Using Eq. (15), the parameter  $c$  for the production stage can be obtained through the following formulation:

$$c = \frac{-(\sigma_H - \sigma_h + P_w - \sigma_c) + \sqrt{(\sigma_H - \sigma_h + P_w - \sigma_c)^2 + 16\sigma_H P_w}}{4\sigma_H} \quad (16)$$

Having the parameter  $c$  calculated from Eqs. (14) and (16), the volume of sand produced during drilling and depletion stages can be obtained from Eq. (11).

### 2.1.3. Mogi–Coulomb criterion

Mogi (1971) proposed a failure criterion formulated below:

$$\tau_{oct} = f(\sigma_{m,2}) \quad (17)$$

where  $\sigma_{m,2}$  and  $\tau_{oct}$  are, respectively, the effective mean stress and octahedral shear stress, while  $f$  is a power-law function. Parameters included in the Mogi’s criterion cannot be simply related to the Coulomb strength parameters,  $c$  and  $\phi$  (Colmenares and Zoback, 2002). Thus, Al-Ajmi and Zimmerman (2005) recommended that the parameter  $f$  can be a linear function following the form of:

$$\tau_{oct} = x + y\sigma_{m,2} \quad (18)$$

where

$$x = \frac{2\sqrt{2}}{3}S_0 \cos \phi \quad (19)$$

$$y = \frac{2\sqrt{2}}{3}S_0 \sin \phi \quad (20)$$

To determine the parameter  $c$  during drilling using the Mogi–Coulomb criterion, the worst case scenario for shear failure is again applied. This means that the tangential ( $\sigma_A$ ), axial ( $\sigma_z$ ) and radial ( $\sigma_r$ ) stresses are, respectively, the maximum, intermediate and minimum principal stresses around the borehole. The axial stress, in this situation, is estimated as

$$\sigma_z = \sigma_v + 2\mu(\sigma_H - \sigma_h) \quad (21)$$

where  $\sigma_v$  is the vertical stress.

The parameter  $c$  can then be estimated as

$$c = \frac{-N + \sqrt{N^2 + 16P_w\sigma_H}}{8\sigma_H} \quad (22)$$

where

$$N = \frac{-\left[\left(\frac{y^2}{2}\sigma_z - 2P_w - 2\sigma_z\right) - ab\right] + \sqrt{\left[\left(\frac{y^2}{2}\sigma_z - 2P_w - 2\sigma_z\right) - ab\right]^2 - \left(\frac{8}{9} - 2y^2\right)F}}{\frac{8}{9} - 2y^2} - \sigma_H + \sigma_h - P_w \quad (23)$$

$$F = \left(\frac{2}{9} - \frac{y^2}{4}\right)\sigma_z + \frac{2}{9}P_w - 2\sigma_zP_w - x^2 + xyP_w \quad (24)$$

At the initial stage of production, however, the radial stress was assumed to be zero ( $\sigma_r = 0$ ) and the parameter  $c$  was formulated as

$$c = \frac{-M + \sqrt{M^2 - 16\sigma_H P_w}}{8\sigma_H} \quad (25)$$

where

$$M = \frac{2\sigma_z + \sqrt{2\sigma_z - 4\left(\frac{2}{9} - \frac{y^2}{4}\right)\frac{2}{9}\sigma_z - x^2}}{\frac{8}{9} - 2y^2} - \sigma_H + \sigma_h - P_w \quad (26)$$

With the parameter  $c$  defined for drilling (Eq. (22)) and depletion (Eq. (25)), the volume of produced sand can be estimated using Eq. (11). As it was indicated earlier, the equations developed for estimation of the parameter  $c$  give the changes in the borehole shape at the initial stage of production. During production, however, the magnitude of horizontal stresses changes as the pore pressure decreases. Aadnoy (1991) derived a model to consider the changes in the magnitude of horizontal stresses as a function of the pore pressure. Aadnoy and Kaarstad (2010) used that model to see the effect of the pore pressure on sand production. The model is formulated by

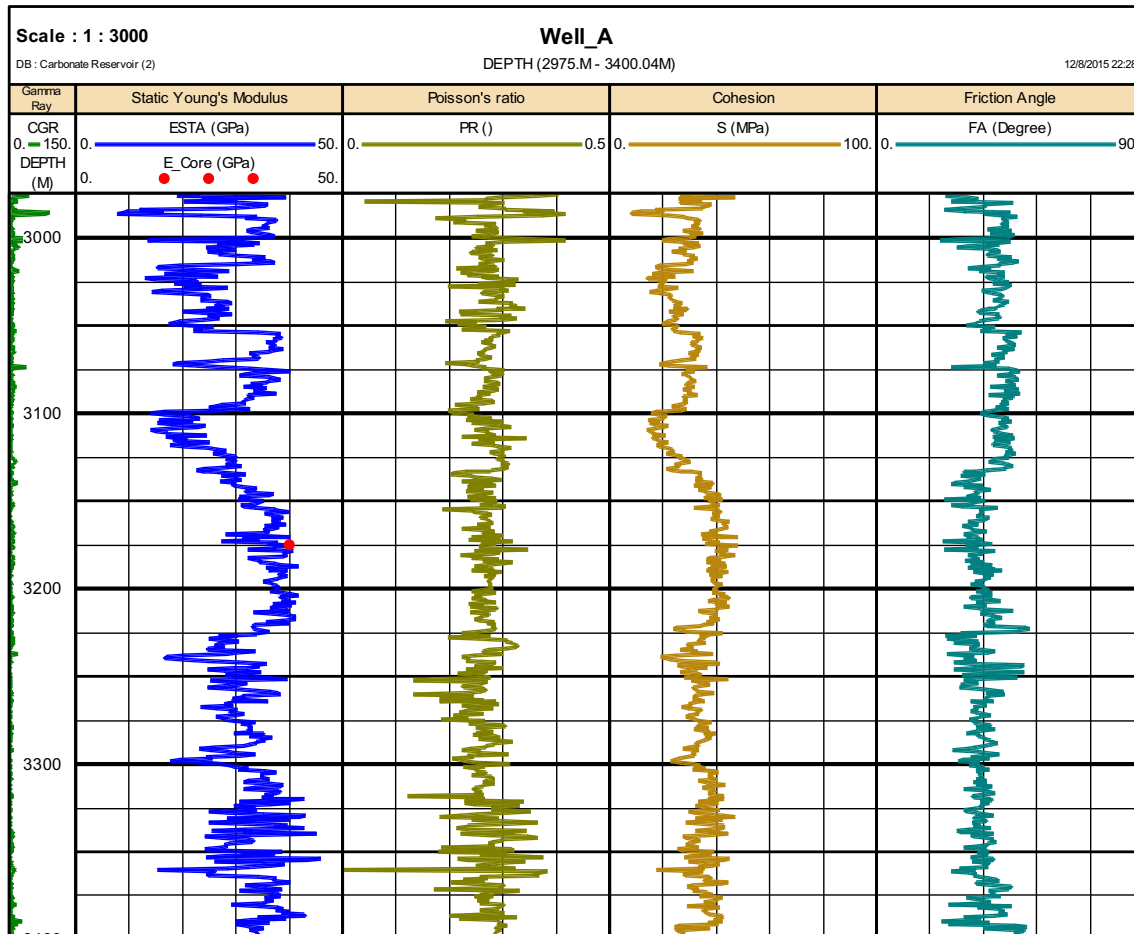


Fig. 4. Estimated static Young's modulus, Poisson's ratio, cohesion, and friction angle of formations in Well A.

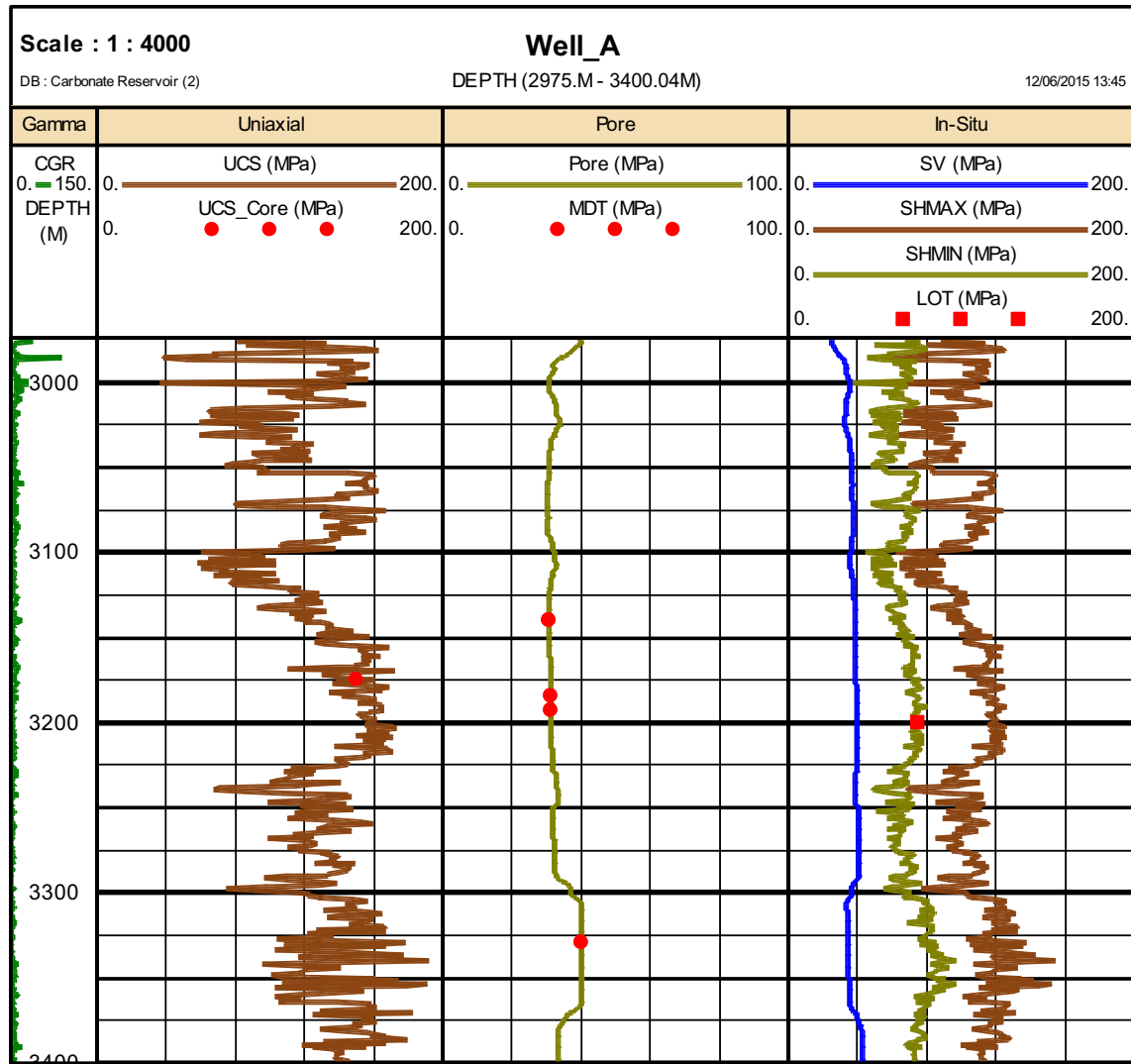


Fig. 5. Estimated UCS, pore pressure and in-situ principal effective stresses in Well A.

$$\sigma_h^* = \sigma_h - \frac{1 - 2\nu}{1 - \nu} (P_o - P_o^*) \quad (27)$$

$$\sigma_H^* = \sigma_H - \frac{1 - 2\nu}{1 - \nu} (P_o - P_o^*) \quad (28)$$

where  $\sigma_h^*$  is the updated minimum horizontal stress,  $\sigma_H^*$  is the updated maximum horizontal stress,  $P_o$  is the initial pore pressure,  $P_o^*$  is the pore pressure of the reservoir at any stage of depletion, and  $\nu$  is the Poisson's ratio.

Substituting the values of in-situ stresses calculated from Eqs. (27) and (28) into Eqs. (10), (16) and (25), the volume of sand/solid production can be estimated at any stages of depletion. It should be noted that to develop the equations presented in this section, it was assumed that the sand production takes place first during drilling until a stable elliptical hole is obtained. This is followed by further changes in the shape of the hole, as depletion initiates and the pore pressure decreases. However, the sanding phenomenon during depletion is a slow process, and the borehole collapse may not take place instantly. Besides, the occurrence of sanding during

drilling may not happen again from the same interval during depletion.

### 3. Case study

In this section, a well with the potential of solid/sand production located in the south of Iran is taken into account to evaluate the application of the proposed methodology. This well, referred to as Well A, is a vertical and onshore well but its name cannot be released due to confidential reasons.

The field of this study is located at offshore of Khuzestan, close to the boundary of Iran and Iraq, which is characterized by a very gentle N–S to NE–SW trending anticline in the South-East, and a NW–SE trending fold in the North-East (Abdollahie Fard et al., 2006). Its structure belongs to the stable shelf of the Arabian Platform and there are limited geological outcrops from subsurface structures which can be evaluated on the surface (Berberian, 1995). This field is one of the richest petroleum systems in the Middle East, having Gurpi, Khazdumi and Gadvan source rocks and Lurestan, Asmari, Khuzestan, Fahliyan, and Khami/Bangestan reservoirs. Field data obtained from this structure have revealed unconformities

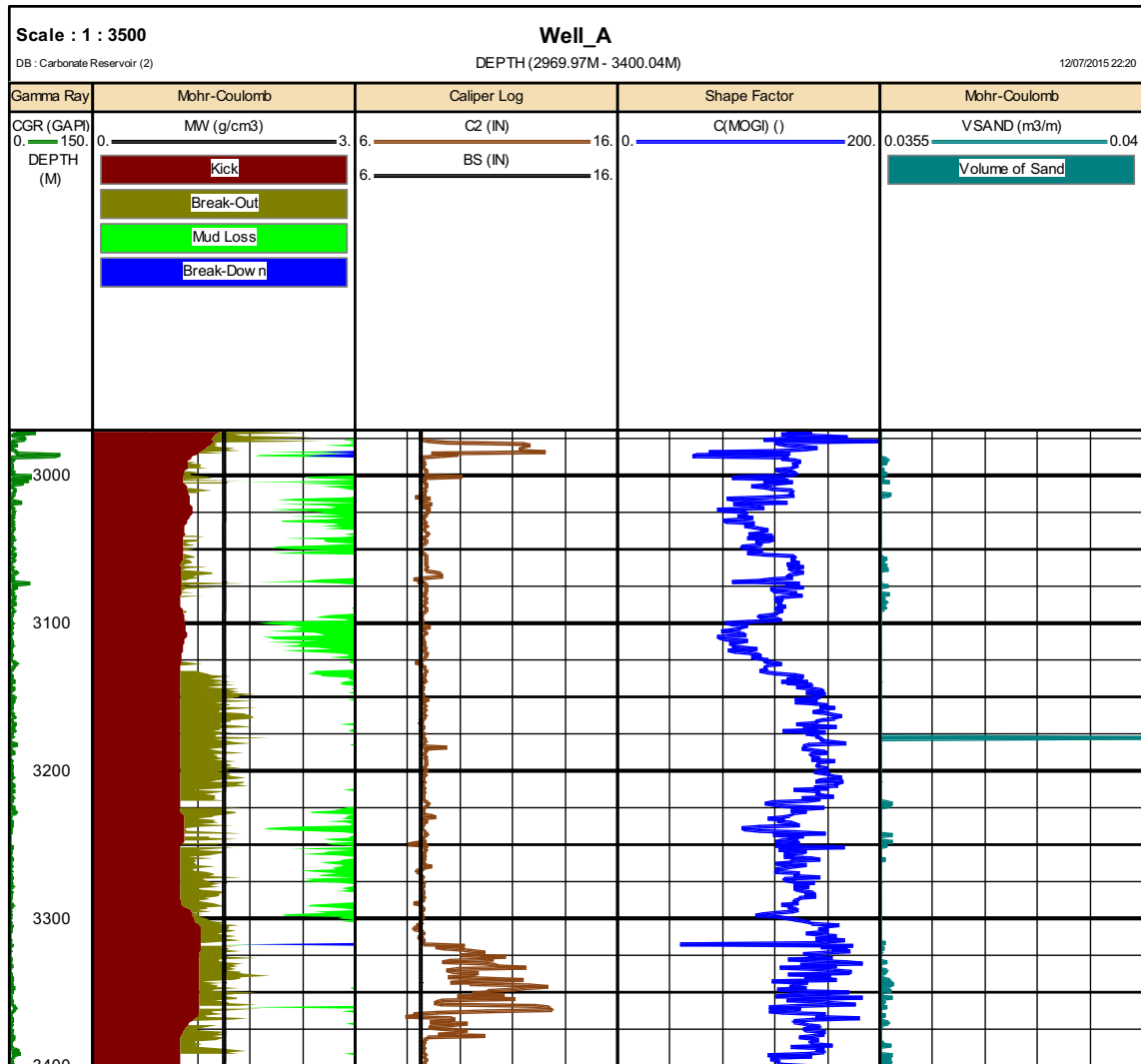


Fig. 6. Shear failure, shape factor and the volume of sand predicted by the Mohr–Coulomb criterion.

and erosional surfaces due to the uplifting of basement horsts. The reservoir in the field has been formed in argillaceous limestone with shaly intercalations. Fig. 2 shows the geological stratigraphy of the field. Fig. 3 shows the logs used for the purpose of this study, including the gamma ray, compressional and shear sonic logs, density and porosity logs as well as resistivity logs. As can be seen in Fig. 3, the reservoir is located in limestone formations within the intervals of 3012–3050 m and 3100–3150 m.

#### 4. Estimation of input parameters

In this section, the input parameters required to apply the proposed methodology are estimated using the well and field data. These parameters consist of the elastic parameters and strength of rocks as well as the pore pressure and in-situ stresses. The details of the principles and correlations used in this paper for estimates of the above parameters have already been reported in the literature (e.g. Maleki et al., 2014; Gholami et al., 2015a, b), and the output results corresponding to Well A were only presented.

Characterizations of the geomechanical parameters were started by estimates of elastic parameters (i.e. Young's modulus and

Poisson's ratio) using dynamic elastic formulations presented by Fjaer et al. (2008). The dynamic to static conversion of the Young's modulus was then done using the correlation proposed by Wang (2000a). It should be noticed that the dynamic and static Poisson's ratios were equal due to the high Young's modulus and in-situ stress in the field (Wang, 2000b). Fig. 4 shows the static Young's modulus and Poisson's ratio estimated and calibrated against the core samples.

There are few correlations which can be used to estimate the friction angle, but the one proposed by Plumb (1994) was used for the purpose of this study due to its proven ability in providing reliable results (Gholami et al., 2015c). The fourth track of Fig. 4 shows the friction angle estimated from the above analysis. The UCS of rocks, however, was estimated using the correlation proposed by Bradford et al. (1998) through the use of the static Young's modulus. The estimated UCS log was then calibrated against the laboratory core test data. The second track of Fig. 5 displays the estimated UCS log where a good match between the estimated log and laboratory data is observed.

The pore pressure was estimated using Eaton's equation (Eaton, 1975) based on the inherent relationship of the pore pressure with



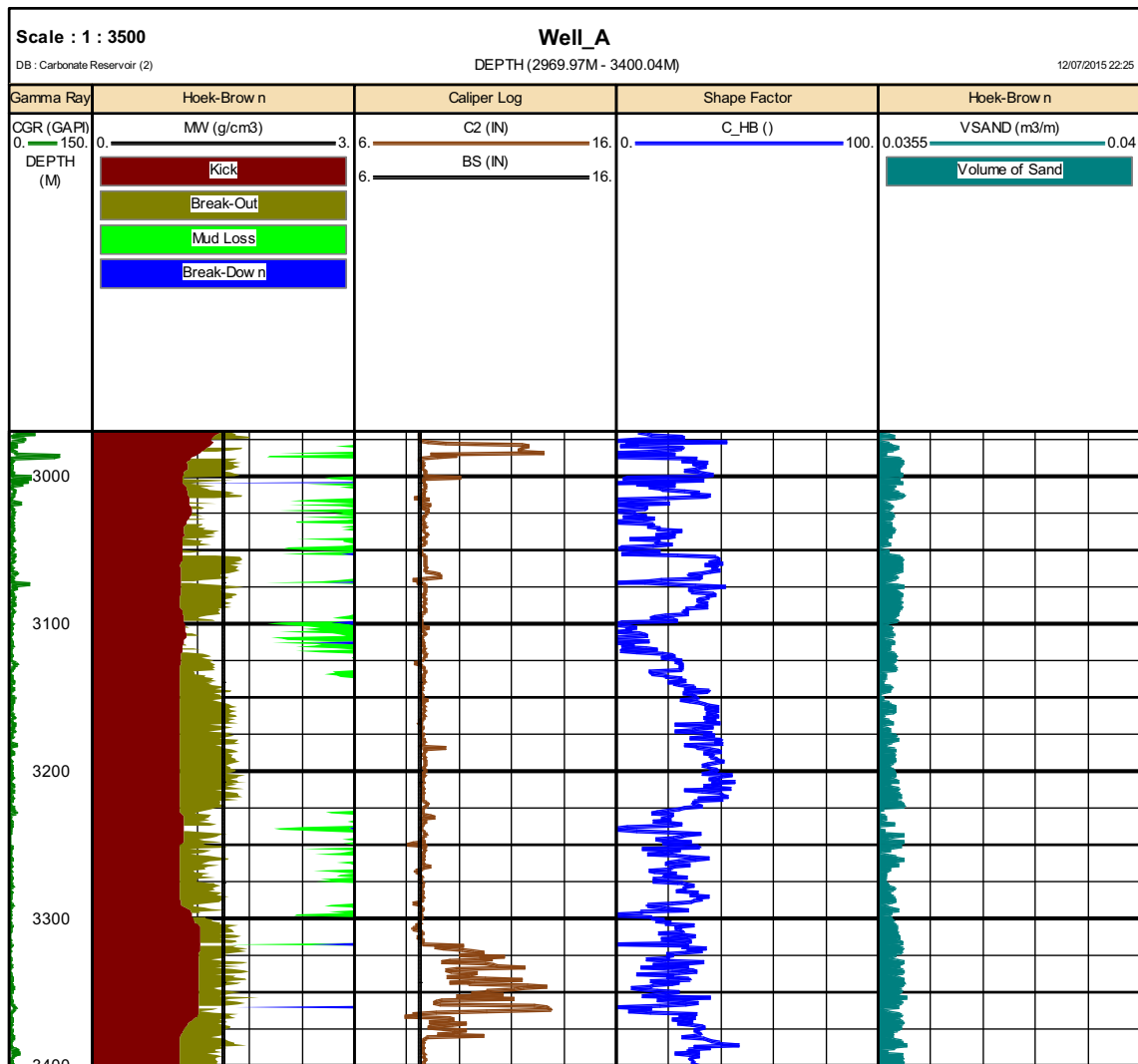


Fig. 7. Shear failure, shape factor and volume of sand predicted by the Hoek–Brown criterion.

P-wave velocity data (sonic log). The pore pressure log was calibrated against modular dynamic formation tester (MDT) data. The estimated pore pressure profile is shown in the third track of Fig. 5.

The vertical stress ( $\sigma_v$ ) was estimated by integrating the bulk density, acceleration, and depth (Fjaer et al., 2008). The magnitude of horizontal stresses was determined using the poroelastic equations (Gholami et al., 2015a, b). The leak-off test (LOT) data were used to calibrate the magnitude of the minimum horizontal stress while failures (break-out) observed in the caliper logs were employed to fix the magnitude of the maximum horizontal stress. The last track of Fig. 5 gives the magnitude of the effective vertical ( $S_v$ ,  $\sigma_v$ ), minimum horizontal ( $S_{hmin}$ ,  $\sigma_{hmin}$ ) and maximum horizontal ( $S_{Hmax}$ ,  $\sigma_{Hmax}$ ) stresses. As shown in this figure, the stress regime in the field is reversed (i.e.  $\sigma_v < \sigma_{hmin} < \sigma_{Hmax}$ ).

## 5. Sand volume calculations

### 5.1. During drilling

An excessive sand/solid production has been reported in the field of current study during the drilling and production stages

while the source of sanding in these two phases was quite different. According to the field and drilling reports, sand was produced from shale and tight formations during drilling while fractured limestone reservoirs were the origin of sanding during depletion. Having the details of the sand production in different stages of the well development, the methodology presented earlier was applied to assess its applicability in predicting the sanding during the drilling operation. The results obtained from this analysis are shown in Figs. 6–8 for different criteria.

Comparing the predictions provided with the breakouts observed in the caliper log, it is found that almost all of the failure criteria are able to provide reasonable results, even though the prediction made by the Mogi–Coulomb criterion is closer to the reality. However, the objective of current study is to evaluate the efficiency of these criteria in prediction of the shape factor and changes in the diameter of the borehole. As is indicated earlier, the volume changes, as a result of the enlargement of the borehole, are related to the volume of sand that will be produced during drilling. Thus, the shape factor parameter  $c$  corresponding to different criteria is estimated from Eqs. (8), (14) and (22) and plotted along with the volume of produced sand estimated from Eq. (11), in the last two tracks of Figs. 6–8.

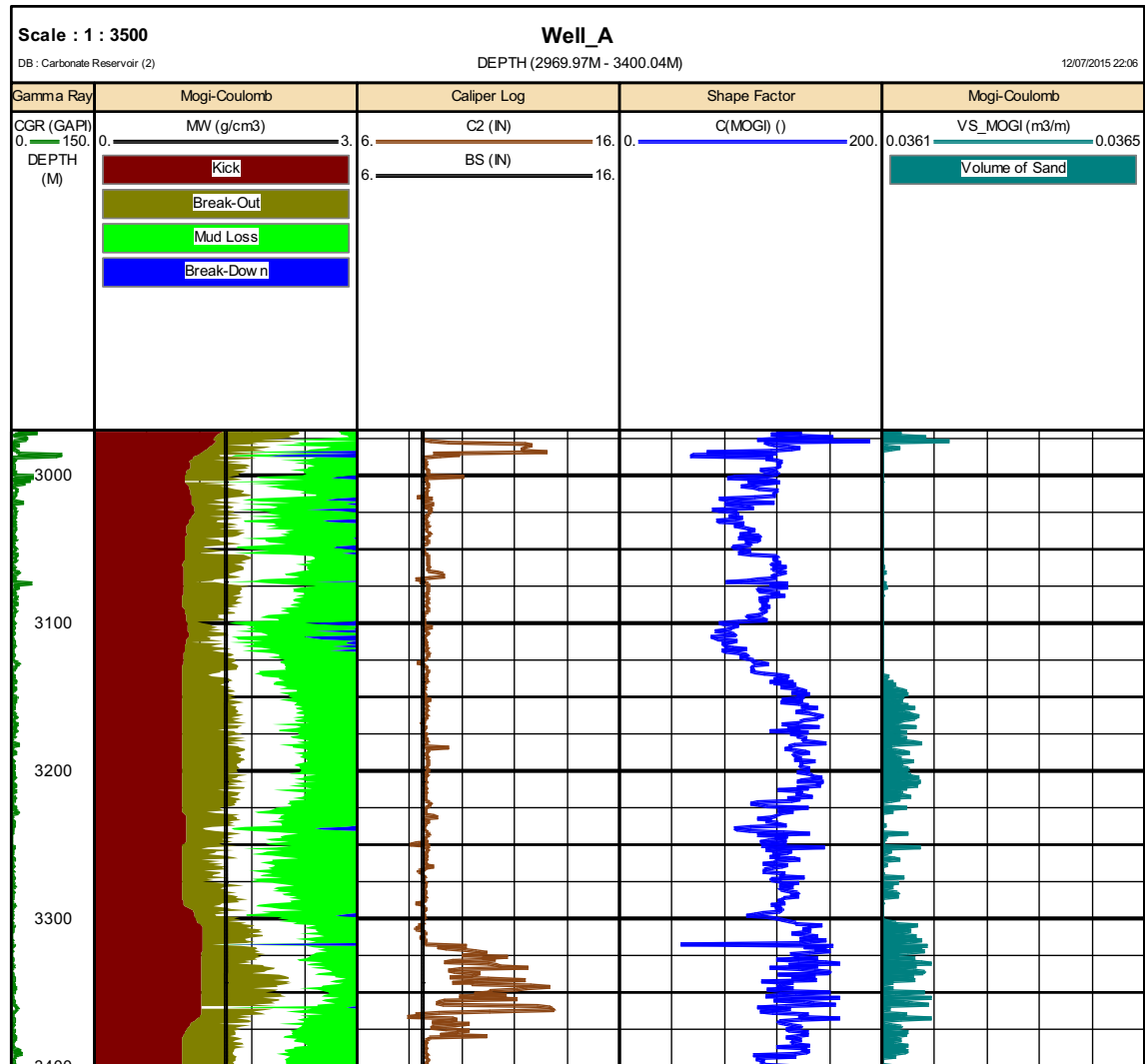


Fig. 8. Shear failure, shape factor and volume of sand predicted by the Mogi–Coulomb criterion.

One can conclude that the shape factor would be different depending on the ability of the criteria in providing a reasonable prediction of shear failure induced on the borehole wall. As it can be seen, the volume of sand has been estimated for the intervals where size of the borehole is larger than its initial value. Having a close look into the estimations provided, it can be concluded that the volume of sand/solid estimated by the Mogi–Coulomb criterion is closer to the reality as it shows a better correlation with the wellbore ovalisation observed in the caliper log. This might be related to the fact that the effect of the intermediate principal stress was taken into account in the criterion. However, the estimation made by the Hoek-Brown is not very far from the reality and can still be justified by considering the fact that it has a two-dimensional nonlinear equation. The prediction provided by the Mohr–Coulomb criterion, however, seems to be unrealistic, especially in the interval where a huge breakout is observed in the caliper log.

From Fig. 8, the total volume of the sand produced based on the Mogi–Coulomb criterion is approximately  $6.87 \text{ m}^3$  which is by far the closest prediction to what has been reported in the drilling reports.

## 5.2. During depletion

As it is indicated earlier, the reservoir in this field is producing from the limestone formations within the intervals of 3012–3050 m and 3100–3150 m. There is no report of solid production from the reservoir intervals during drilling due to the consolidated nature of the formations and a high reservoir pore pressures. However, depletion causes the reservoir pressure to drop from 40 MPa to 25 MPa after 1 year of production. This significant change in the variation of the pore pressure has remarkably increased the effective horizontal in-situ stresses and caused the solid production to start. In fact, the UCS and the cohesion of the reservoir intervals are on average 80 MPa and 20 MPa, respectively (see Figs. 5 and 6). These values do not appear to be very low but not high enough to resist against the excessive in-situ stresses induced, due to a large reduction in the pore pressure.

To calculate the volume of produced solid across the reservoir intervals, it is necessary to calculate the changes in the magnitude of effective horizontal stresses due to depletion. Considering the geomechanical parameters estimated earlier (Figs. 4 and 5), the average magnitudes of the Poisson's ratio and effective minimum

and maximum horizontal stresses in the reservoir intervals were considered to be 0.3, 60 MPa, and 78 MPa, respectively. Substituting the above-mentioned values into Eqs. (27) and (28), the magnitudes of effective minimum and maximum horizontal stresses were obtained to be 68.5 MPa and 86.5 MPa, respectively.

The parameter  $c$  was then calculated based on the Mogi–Coulomb criterion (Eq. (25)) due to its better efficiency in prediction of sanding during drilling. The results obtained indicated a 1.5 cm enlargement in the size of the wellbore resulting in a total amount of 1.1 m<sup>3</sup> produced sands. The calculations indicated that a volume of 0.3 m<sup>3</sup> was produced from the interval of 3012–3050 m with the remaining of 0.8 m<sup>3</sup> being produced from the interval of 3100–3150 m. In the above calculations, the parameter  $b$ , the radius of the intact borehole (see Fig. 1), is assumed as 0.216 m, as shown in the third tracks of Figs. 6–8.

The production reports from this field has estimated an average of 0.9 m<sup>3</sup> solid being produced from the reservoir intervals after one year, which resulted in using gravel pack to stop sanding.

## 6. Conclusions

In this study, a new approach based on the changes in the diameter of the borehole was presented to estimate the volume of sand produced during drilling and production. A shape factor parameter was introduced to capture the change in the geometry of the borehole taken place due to the excessive hoop stress. Three failure criteria were used to develop equations for determination of the shape factor and the models were applied to a well located in the south of Iran. The results obtained indicated that taking the effect of the intermediate stress into account by employing a three-dimensional failure criterion can provide reliable results when it comes to the prediction of shear failure and volume of sand. The close agreement between the values predicted by the presented approach and those given in the drilling and production reports indicates the applicability of the model. However, the approach presented requires determination of the geomechanical parameters before initiation of depletion due to the variation of the pore pressure. This means that it would be hard to apply this methodology directly into production stage to predict sanding.

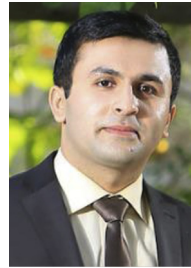
## Conflict of interest

The authors wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

## References

- Aadnoy BS. Effects of reservoir depletion on borehole stability. *Journal of Petroleum Science and Engineering* 1991;6(1):57–61.
- Aadnoy BS, Kaarstad E. History model for sand production during depletion. In: *Proceedings of the SPE EUROPEC/EAGE Annual Conference and Exhibition*. Barcelona, Spain: Society of Petroleum Engineers; 2010. p. 14–7.
- Abass HH, Nasr-El-Din HA, BaTaweel MH. Sand control: sand characterization, failure mechanisms, and completion methods. In: *Proceedings of the SPE Annual Technical Conference and Exhibition*. San Antonio, Texas: Society of Petroleum Engineers; 2002. p. 1–8.
- Abdollahi Fard I, Braathen A, Mokhtari M, Alavi SA. Interaction of the Zagros fold-thrust belt and the Arabian-type, deep-seated folds in the Abadan Plain and the Dezful Embayment, SW Iran. *Petroleum Geoscience* 2006;12(4):347–62.
- Addis MA, Gunningham MC, Brassart PC. Sand quantification: the impact on completion design, facilities design and risk evaluation. In: *SPE Annual Technical Conference and Exhibition*. Denver: Society of Petroleum Engineers; 2008. p. 1–18.
- Alavi M. Regional stratigraphy of the Zagros fold-thrust belt of Iran and its foreland evolution. *American Journal of Science* 2004;304(1):1–20.
- Al-Ajmi AM, Zimmerman RW. Relationship between the parameters of the Mogi and Coulomb failure criterion. *International Journal of Rock Mechanics and Mining Sciences* 2005;42(3):431–9.
- Berberian M. Master “blind” thrust faults hidden under the Zagros folds: active basement tectonics and surface morphotectonics. *Tectonophysics* 1995;241(3/4):193–224.
- Bradford IDR, Fuller J, Thompson PJ, Walsgrove TR. Benefits of assessing the solids production risk in a North Sea reservoir using elastoplastic modelling. In: *SPE/ISRM 47360, Proceedings of Eurock '98 – SPE/ISRM Rock Mechanics in Petroleum Engineering*. Trondheim, Norway: Society of Petroleum Engineers; 1998. p. 261–9.
- Bratli RK, Risnes R. Stability and failure of sand arches. *Society of Petroleum Engineers Journal* 1981;21(2):236–48.
- Cerasi P, Papamichos E, Stenebraten JF. Quantitative sand production prediction: friction-dominated flow model. In: *SPE Latin American and Caribbean Petroleum Engineering Conference*. Rio de Janeiro: Society of Petroleum Engineers; 2005. p. 1–10.
- Colmenares LB, Zoback MD. A statistical evaluation of intact rock failure criteria constrained by polyaxial test data for five different rocks. *International Journal of Rock Mechanics and Mining Sciences* 2002;39(6):695–729.
- Detournay C, Tan C, Wu B. Modeling the mechanism and rate of sand production using FLAC. In: *Proceedings of the 4th International FLAC Symposium on Numerical Modeling in Geomechanics*. Minneapolis: Itasca Consulting Group; 2006. p. 8–10.
- Eaton BA. The equation for geopressure prediction from well logs. *Society of Petroleum Engineers of AIME*; 1975. SPE 5544.
- Ewy RT, Ray P, Bovberg CA, Norman PD, Goodman HE. Openhole stability and sanding predictions by 3D extrapolation from hole collapse tests. *SPE Drilling & Completion* 2001;16(4):243–51.
- Fjaer E, Holt RM, Horsrud P, Raean AM, Risnes R. Chapter 3 geological aspects of petroleum related rock mechanics. *Developments in Petroleum Science* 2008;53:103–33.
- Gholami R, Rasouli V, Aadnoy B, Mohammadnejad M. Geomechanical and numerical studies of casing in reservoir with solid production. *Rock Mechanics and Rock Engineering* 2015. <http://dx.doi.org/10.1007/s00603-015-0828-5>.
- Gholami R, Rasouli V, Aadnoy B, Mohammadi R. Application of in-situ stress estimation methods in wellbore stability analysis under isotropic and anisotropic conditions. *Journal of Geophysics and Engineering* 2015b;12(4):1–17.
- Gholami R, Rabie M, Rasouli V, Aadnoy B, Fakhari N. Application of quantitative risk assessment in wellbore stability analysis. *Journal of Petroleum Science and Engineering* 2015c;135:185–200.
- Hoek E, Brown ET. *Underground excavations in rock*. London: Institution of Mining and Metallurgy; 1980.
- Hoek E, Brown ET. Practical estimates of rock mass strength. *International Journal of Rock Mechanics and Mining Sciences* 1997;34(8):1165–86.
- Hoek E, Carranza-Torres CT, Corkum B. Hoek–Brown failure criterion — 2002 edition. In: *Proceedings of 5th North American Rock Mechanics Symposium*. Toronto, Canada: Rocscience; 2002. p. 267–73.
- Hoek E, Kaiser PK, Bawden WF. *Support of underground excavations in hard rock*. Rotterdam: A.A. Balkema; 1995. p. 225.
- Homke S, Vergés J, Serra-Kiel J, Bernaola G, Sharp I, Garcés M, Montero-Verdu I, Karpuz R, Goodarzi MH. Late Cretaceous–Paleocene formation of the proto-Zagros foreland basin, Lurestan Province, SW Iran. *Geological Society of America Bulletin* 2009;121:963–78.
- James GA, Wynd JG. Stratigraphic nomenclature of Iranian oil consortium agreement area. *The American Association of Petroleum Geologists Bulletin* 1965;49(12):2182–245.
- Kooijman AP, van den Hoek PJ, De Bree Ph, Kenter CJ, Zheng BVZ, Khodaverdian M. Horizontal wellbore stability and sand production in weakly consolidated sandstone. In: *SPE Annual Technical Conference and Exhibition*. Denver, Colorado: Society of Petroleum Engineers; 1996. p. 35–48.
- Lamorde M, Somerville JM, Hamilton AS. Application of the yield energy approach to prediction of sand debris production in reservoir sandstones. In: *SPE Nigeria Annual International Conference and Exhibition*. Lagos, Nigeria: Society of Petroleum Engineers; 2014. p. 1–21.
- Lee YK, Bobet A. Instantaneous friction angle and cohesion of 2-D and 3-D Hoek–Brown rock failure criteria in terms of stress invariants. *Rock Mechanics and Rock Engineering* 2014;47(2):371–85.
- Lekhnitskii SG. *Anisotropic plates* [Tsai SW, Cheron T, Trans.]. New York: Gordon and Breach; 1968.
- Maleki S, Gholami R, Rasouli V, Moradzadeh A, Riabi RG, Sadaghzadeh F. Comparison of different failure criteria in prediction of safe mud weight window in drilling practice. *Earth-Science Reviews* 2014;136:36–58.
- McLellan PJ, Wang Y. Predicting the effects of pore pressure penetration on the extent of wellbore instability: application of a versatile poro-elastoplastic model. In: *Proceedings of Eurock '94 – SPE/ISRM Rock Mechanics in Petroleum Engineering*. Delft, Netherlands: Society of Petroleum Engineers; 1994. p. 205–14.
- Mogi K. Fracture and flow of rocks under high triaxial compression. *Journal of Geophysical Research* 1971;76(5):1255–69.
- Morita N, Whitfill DL, Fedde OP, Lovik TH. Parametric study of sand-production prediction: analytical approach. *SPE Production Engineering* 1989;4(1):25–33.
- Nouri A, Vaziri H, Belhaj H, Islam R. Effect of volumetric failure on sand production in oil-wellbore. In: *SPE Asia Pacific Oil and Gas Conference and Exhibition*. Jakarta, Indonesia: Society of Petroleum Engineers; 2003. p. 1–8.
- Nouri A, Vaziri H, Belhaj H, Islam R. Sand-production prediction: a new set of criteria for modeling based on large-scale transient experiments and numerical investigation. *SPE Journal* 2006;11(2):26–9.

- Nouri A, Vaziri H, Belhaj H, Islam R. Comprehensive transient modeling of sand production in horizontal wellbores. *SPE Journal* 2007;12(4):1–9.
- Osisanya OS. Practical guidelines for predicting sand production. In: Nigeria Annual International Conference and Exhibition. Tinapa – Calabar, Nigeria: Society of Petroleum Engineers; 2010. p. 1–8.
- Palmer ID, McLennan JD, Vaziri HH. Cavity-like completions in weak sands. In: SPE International Symposium on Formation Damage Control. Lafayette, Louisiana: Society of Petroleum Engineers; 2000. p. 1–9.
- Papamichos E, Malmanger EM. A sand erosion model for volumetric sand predictions in a North Sea reservoir. In: Latin American and Caribbean Petroleum Engineering Conference. Caracas, Venezuela: Society of Petroleum Engineers; 1999. p. 2–9.
- Papamichos E, Furui K. Sand production initiation criteria and their validation. In: 47th U.S. Rock Mechanics/Geomechanics Symposium. San Francisco, California: American Rock Mechanics Association; 2013. p. 1–9.
- Plumb RA. Influence of composition and texture on the failure properties of clastic rocks. In: Eurocks 94, Rock Mechanics in Petroleum Engineering Conference. Delft, Netherlands: Society of Petroleum Engineers; 1994. p. 13–20.
- Risnes R, Bratli RK, Horsrud P. Sand stresses around a wellbore. *Society of Petroleum Engineers Journal* 1982;22(6):883–98.
- van den Hoek PJ, Kooijman AP, de Bree Ph, Kenter CJ, Sellmeyer HJ, Willson SM. Mechanisms of downhole sand cavity re-stabilisation in weakly consolidated sandstones. In: SPE European Petroleum Conference. Paris, France: Society of Petroleum Engineers; 2000. p. 1–9.
- Vaziri H, Lemoine E, Palmer I, McLennan J, Islam R. How can sand production yield a several-fold increase in productivity: experimental and field data. In: SPE Annual Technical Conference and Exhibition. Dallas, Texas: Society of Petroleum Engineers; 2000. p. 1–12.
- Vaziri H, Barree B, Xiao Y, Palmer I, Kutas M. What is the magic of water in producing sand?. In: SPE Annual Technical Conference and Exhibition. San Antonio, Texas: Society of Petroleum Engineers; 2002. p. 1–13.
- Veeken CAM, Davies DR, Kenter CJ, Kooijman AP. Sand production prediction review: developing an integrated approach. In: SPE Annual Technical Conference and Exhibition. Dallas, Texas: Society of Petroleum Engineers; 1991. p. 335–46.
- Wang HF. Theory of linear poroelasticity. Princeton: Princeton University Press; 2000a.
- Wang Z. Dynamic versus static elastic properties of reservoir rocks. In: Wang ZJ, Nur A, editors. Seismic and acoustic velocities in reservoir rocks. Tulsa: Society of Exploration Geophysicists; 2000b. p. 531–9.
- Wang Y, Dusseault MB. Borehole yield and hydraulic fracture initiation in poorly consolidated rock strata – Part II. Permeable media. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts* 1991;28(4):247–60.
- Wang Y, Papamichos E. Sand prediction by different criteria and a validation by a perforated test in a sandstone. In: SPE Heavy Oil Conference Canada. Calgary, Alberta, Canada: Society of Petroleum Engineers; 2012. p. 2–9.
- Watson K, Jones C. FEA modeling of expandable sand screens interactions with rock formations. In: Simula Customer Conference, SCC 2009. London: Dassault System; 2009. p. 1–12.
- Weingarten JS, Perkins TK. Prediction of sand production in gas wells: methods and Gulf of Mexico case studies. *Journal of Petroleum Technology* 1995;47(7):596–600.



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