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Numerical simulations of wellbore stability in under-balanced-drilling wells

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ABSTRACT

Drilling underbalanced is often used to prevent formation damage, avoid lost circulation, and increase rate of penetration. However, it is also risky and may lead to wellbore collapse due to lack of positive support provided by the hydrostratic wellbore fluid column. Hence, the application of underbalanced drilling (UBD) should be evaluated thoroughly through the use of in-situ stresses and rock mechanical properties to estimate under what hydraulic drilling conditions the wellbore is stable.

This paper presents numerical simulations for wellbore stability analysis in two depleted Iranian fields, named herein as field A and B. The simulations were executed both in Finite-Explicit and Finite-Element codes to cross check the results.

Depleted Iranian fractured carbonate fields are suffering from severe wellbore stability problems and lost circulation during overbalanced drilling conditions. The application of UBD in these fields with a pressure less than formation pore pressure brought on new wellbore stability problems like risk of shear failure and collapse of borehole wall. Using good geomechanical model description matching field characteristics in conjunction with rock failure criteria in some cases may lead to a good prediction for avoiding wellbore stability problems and choosing the optimum mud weight window. By analyzing cores, log and triaxial rock mechanical data, an elastoplastic model combined with a finite explicit code was used in the wellbore stability analysis to estimatimate an optimum Equivalent Circulating Density (ECD) for these fields. Compared to some actual field data it was observed that using an elastoplastic constitutive model would be sufficient to analyze mechanical wellbore stability in these fields.

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1. Introduction

Underground formations are subjected to a vertical compressive stress caused by the weight of the overlying strata and horizontal stresses due to the confining lateral restraints. Under the action of these *in situ* stresses, prior to drilling a borehole, the rock mass is in a state of equilibrium that will be destroyed by the excavation. When a borehole is drilled, the load carried by the removed rock is then taken by the adjacent rock to re-establish equilibrium. As a result, a stress concentration is produced around the well. If there is no hydrostatic support pressure introduced into the borehole, failure in the formation may take place. Therefore, maintaining equilibrium in the field to prevent rock failure requires the use of a support pressure which is usually provided by the drilling fluid. In order to evaluate the potential for wellbore stability a realistic constitutive model must be used to compute the stresses and strains around a borehole.Out of the numerous published models, the linear elastic model (LEM) is the most common approach. This is due to its simplicity and less required input parameters compared to other models. However, using these simple models in some cases underpredicts the wellbore stable ECD. The LEM based models do not adequately explain the fact that, in many cases the borehole remains stable even if the stress concentration around the borehole exceeds the strength of the formation.

Alternatively, elastoplastic models offer the ability to assess the mechanical integrity of a borehole more realistically. Westergaard (1940) published one of the early works contributing to the knowledge of stress distribution around a borehole, in which an elastoplastic model was developed (Al-Ajmi, 2006). Later works using elasto-plastic models have been published (e.g., Gnirk, 1972; Risnes and Bratli, 1981; Mitchell et al., 1987; Anthony and Crook, 2002). Table 1 shows a summary of the current wellbore stability models (Chen, 2001).

An elastoplastic model for assessing wellbore stability analysis in two depleted carbonate fields are presented in this paper. Based on stability analysis results compared with behavior of the drilling of two UBD horizontal wells in these depleted fields proved the feasibility and accuracy of using an elastoplastic model to predict the operational ECD windows. Although considering behavior of only two wells is not sufficient to conclude that implementing this model for all the carbonate fields will yield similar results, it is suggested that the result of this study can be expanded for use on other fields with similar characteristics.

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Table 1
Current wellbore stability models.

Reference	Model type	Special features
Bradley (1979)	Linear elasticity	Zero tensile strength
Fuh et al. (1988)	No chemical effect	
Aadnoy et al. (1987)	No fluid diffusion	Zero tensile strength
McLean and Addis (1990a,b)	No thermal effect	
Zhou et al. (1996)		
		Truncated Desai's yield function
Santarelli et al. (1986)	Stress dependent linear elasticity	
Detournay and Cheng (1987)	Linear poroelasticity	Vertical well Undrained condition
Yew et al. (1990), Wang and van Kruijsdijk (1996)	Moisture adsorption	
Wang (1998)	Chemical effect and moisture adsorption	Variable Young's modulus
Yew and Lui (1992)	Linear poroelasticity, no chemical effect	
Mody and Hale (1993)	Chemical effect	
		Stress on the wellbore wall
Sherwood (1993)	Chemical effect	Chemical potential of different components
Wang and Papamichos (1994)	Chemical effect	Shale properties vary with water content
Cui et al. (1997)	No chemical effect	Solution in Laplace
Cui et al. (1999)	Time dependency	domain, superposition
	Time dependency	technique
Abousleiman et al. (1995)	Poroviscoelasticity	
McLean and Addis (1990)	Nonlinear elasticity	
Mclellan (May 1996)	Elasto-Plasticity	
McLellan and	Elasto-Plasticity	
Wang (1994)	Plasticity	
Ewy (1999)		
Detournay (1995)	Coupled thermo-hydro-poroelasticity	Drained and undrained conditions
Wang et al. (1996)		
Li et al. (1998)	Thermoporoelasticity	Conductive heat flow
Choi and Tan (1998)	Thermoporoelasticity	
		Numerical validation
Wang and Dusseault (1995)	Thermoporoplastic	

2. Fields background

90% of the discovered fields in Iran are in carbonate reservoirs putting Iran as one of the largest carbonate producers in the world (Abdollahi et al., 2004). Field A and B are located in southern part of Iran. Geological studies combined with the core samples taken from these fields, represented a highly fractured limestone reservoirs with low formation pore pressure gradients. Fig. 1 shows the history of the depletion in the field A. Because of the confidential nature of the studies undertaken in these fields the names are not revealed.

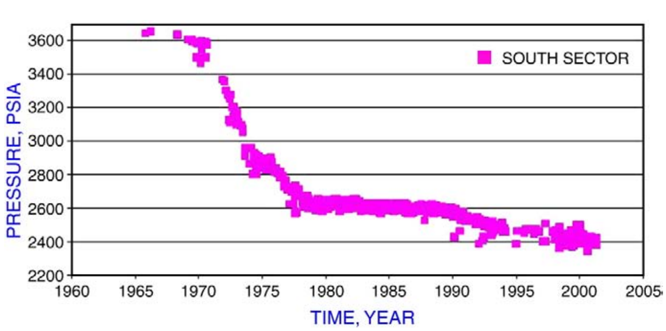

Fig. 1. Depletion history for the field A.

Lost circulation is one of the most severe drilling problems in these fields. So the determination of proper ECD is challenging.

3. ECD as a controllable factor

Some factors which affect wellbore failure can be controlled while others are impossible to control because of the intrinsic properties of earth. The primary factors affecting wellbore stability are listed in Table 2 (Westergaard, 1940). Equivalent Circulating Density (ECD) is the dominant controllable factor in applied wellbore stability analysis. The support pressure offered by the static or dynamic fluid pressure during drilling, simulating, working over or producing of a well, will determine the stress concentration present in the wellbore vicinity (Mclellan, 1996). This paper estimates the optimum ECD for preventing wellbore stability problems in two depleted carbonate fields.

4. Data gathering

The operator was considering two underbalanced horizontal wells in two depleted carbonate fields. The 6 ½ in wellbores were horizontal at an approximate depth of 8687 ft in field A and 6218 ft in field B. Pore pressure gradient was found from DST test analysis for both fields at the mentioned depths and reported as (5.56 Lb/Gal) and (5.68 Lb/Gal) in field A and B respectively.

Usually the most important data for wellbore stability analysis is the rock mechanical data. Knowledge of this type of data in Iranian fields is limited, however for the mentioned fields in this paper some laboratory test were available.

For field A, two laboratory methods were used for determining elastic properties.

- Static (triaxial)
- Dynamic (acoustic)

The preferred method is to perform static triaxial tests on cores since this method provides the most accurate and reliable data.

As a general rule, the dynamic techniques are inaccurate because of poro-elastic influence on sonic wave propagation. Consequently all dynamic test methods must be calibrated to provide reasonable estimates of static values needed for wellbore stability analysis.

Typically with frequency used in laboratory for acoustic measurement, only small scale features dominate the results. So the static young modulus is taken as the more representative value for stability analysis. In general it is found that the static Poisson's ratio usually underestimates the stress in the reservoir, for this reason the dynamic Poisson's ratio was used for analysis.

Table 2
Controllable factors and uncontrollable factors.

Controllable factors	Uncontrollable factors
Equivalent circulating Density(ECD)	In-situ stresses
	Rock lithology
Drilling fluid type	Pore fluid chemistry
Drilling fluid chemistry	Rock porosity, original
Well orientation, direction relative to stress field	Permeability, compressibility
	Initial rock temperature
Mud temperature	Rock strength
Borehole size	Rock mechanical properties
Drill pipe size	Initial pore pressure
Circulating rate	Natural fractures
Open hole time	Rock thermal properties
Drilling operations (tripping, drilling, casing, cementing)	Geothermal gradient

For the second field (B) compressive and shear sonic transit time were used for calculating elastic properties (Eq. (1)). Morales correlation was used to convert dynamic values to static. (Appendix A).

$$V_d = \left(V_P^2 - 2V_S^2\right) \Big/ \left[2\left(V_P^2 - V_S^2\right)\right] \tag{1}$$

Other data were found from a nearby undepleted reservoir, and then adjusted to depleted conditions. Because of the uncertainties in magnitude of cohesions, three different sets of data were used in the wellbore stability analysis. (Table 4).

The total overburden stress gradient was approximated by integration of formation bulk density over depth. (Eq. (2))

$$\sigma_V = \int_0^{D_{\max}} \rho_b g dD \tag{2}$$

Due to poro-elastic effects in these fields, the reservoir depletion will directly affect the horizontal stresses. Fig. 2 shows the stress changes due to poro-elastic effects. Horizontal stresses were measured by the analysis of fracture pressure in similar nearby depleted fields prior to depletion and then corrected to poro-elastic effects. Knowledge of the minimum in-situ stress direction in these fields was limited to poor quality data from oriented caliper logs which defined the directions as approximately N40W in field A and S20N in field B.

The rock mechanical properties for both fields are summarized in Tables 3 and 4.

5. Influence of depletion on field in-situ stress

Normally the pore pressure drops when the fields start producing. The in-situ stress profile of the fields will also drop as the reservoir pore pressure drops. Response of the horizontal stresses due to depletion is very important when drilling wells, because the mud pressure should be balanced less than formation fracturing pressure and more than its collapse pressure to avoid either loss circulation problems or borehole breakouts. For this reason, it is essential to predict horizontal stress changes as the reservoir pressure drops. It is often challenging to predict these changes and there are relatively few fields around the world where a sufficiently good data exists to find the correlation for these changes. Since there was no valid data for the fields under study in this paper, we have used the data in nearby depleted fields in order to correlate the changes in far field stress. Using data from nearby fields we assumed that the response is elastic

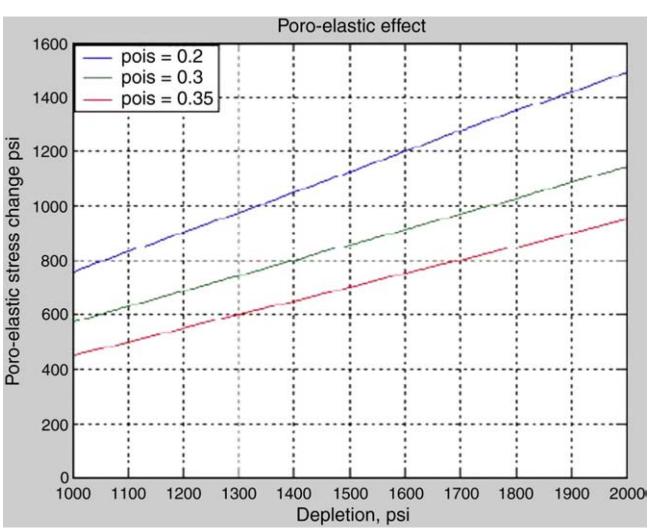

Fig. 2. Poroelastic-effects generated from depletion.

Table 3
Input parameters for wellbore stability analysis in field A.

Poisson's ratio	0.33
Young's modulus(E,10^6 psi)	3.31
Friction angle at peak strength (φ_p)	41.50
Cohesion at peak strength (C_p,psi)	1850
Cohesion at residual strength (C_r, psi)	540
Overburden stress gradient (σ_v, psi/ft)	1.20
Maximum horizontal stress gradient ($\sigma_{H\max}$, psi/ft)	0.81
Minimum horizontal stress gradient ($\sigma_{H\min}$, psi/ft)	0.72

and a correlation parameter (f) (Eq. (3)) was found to be used for predicting true stresses used for simulations.

$$f = \frac{\delta\sigma_h}{\delta p_p} \tag{3}$$

6. Technical approach

Different wellbore stability analysis methods are presented in literature. McLean and Addis (1994) used finite element methods to predict wellbore stability parameters. The use of numerical/analytical models to predict the mechanical behavior of a wellbore requires a number of input parameters to be defined or assessed. Here we have used a finite explicit code named FLAC for conducting wellbore stability simulations . An elastoplastic Mohr–Coulomb failure criteria model is used for assessing state of instability with respect to different ECDs.

Since wellbore orientation and ECD values are the only controllable factors a few assumptions were made;

- Orientation. The vertical direction is assumed to be a principle direction of stress. Because there are some uncertainties to direction of the principle horizontal stresses the worst case scenario was assumed where the horizontal wells are parallel to the maximum horizontal stress direction.
- ECD. This was the only controllable variable and the optimum ECD; considering UBD condition was determined in the field A and B to be less than 5.57 lb/Gal and 5.67 lb/Gal respectively.

A criterion based on size of yielded zone was used in analyzing the risk of borehole instability. Since the yielded zone will be susceptible to spalling due to pressure surges during trips and mechanical erosion by the drillstring, the larger this zone is the greater the likelihood that instability-related problems will occur (Hawkes and McLellan, 1996). (Fig. 3) A parameter often used as a borehole instability risk indicator is the Normalized Yielded Zone Area (NYZA), which is the cross-sectional area of the yielded rock around the borehole divided by the area of the original borehole. Experience has indicated that the onset of borehole instability problems is often associated with NYZAs greater than 1.0, although the critical value for this parameter undoubtly varies depending on the setting and other factors such as well inclination and hole cleaning capacity. More details on this can be found in references (Hawkes and McLellan, 1996, 1997; Hawkes et al., 2000). Simulations for

Table 4
Input parameters for wellbore stability analysis in field B.

Poisson's ratio	0.30
Young's modulus(10^6 psi)	0.66
Friction angle at peak strength (φ_p)	30,35,40
Cohesion at peak strength (C_p, psi)	870,1450,2175
Cohesion at residual strength (C_r, psi)	217,480,620
Overburden stress gradient (σ_v, psi/ft)	1
Maximum horizontal stress gradient ($\sigma_{H\max}$, psi/ft)	0.69
Minimum horizontal stress gradient ($\sigma_{H\min}$, psi/ft)	0.58

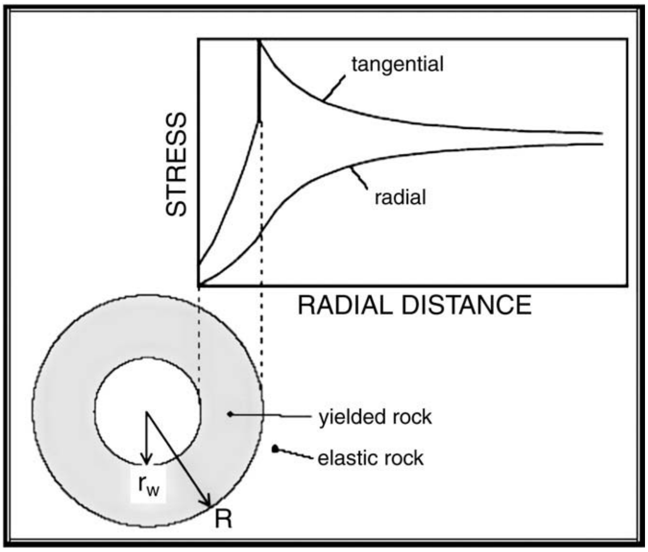

Fig. 3. Development of yielded zone around the wellbore.

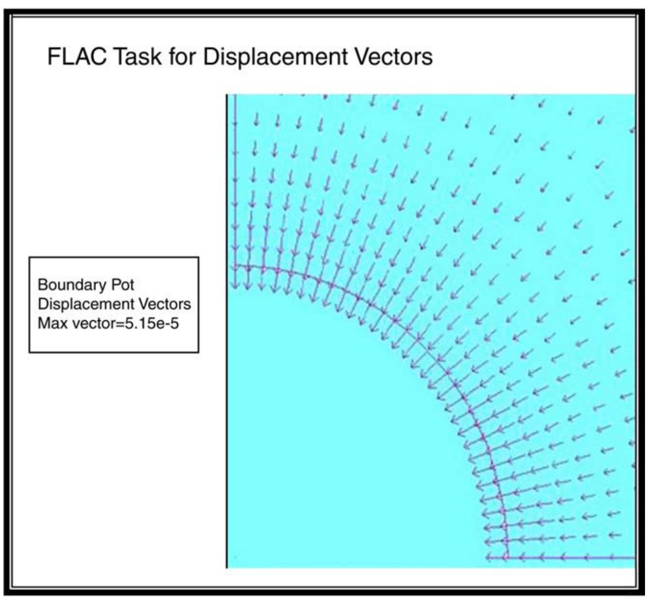

Fig. 4. Maximum displacement generated in FLAC simulations.

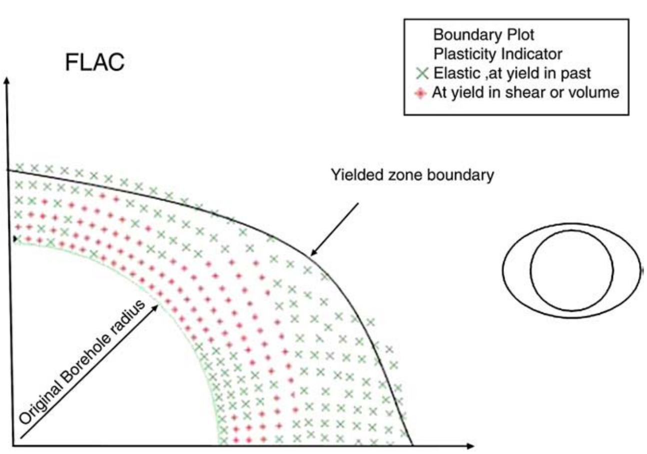

Fig. 5. Predicting yielded zone in FLAC.

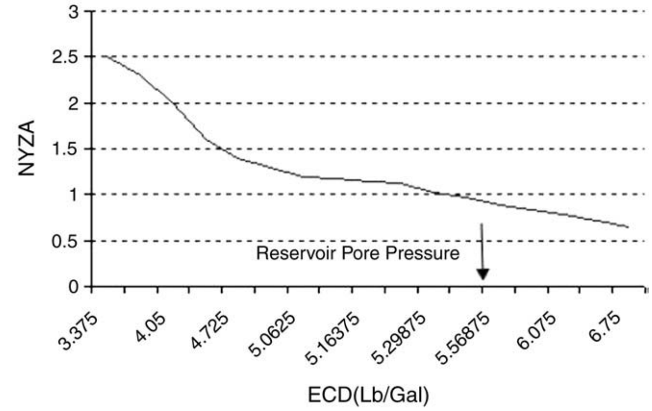

Fig. 6. NYZA versus ECD in field A.

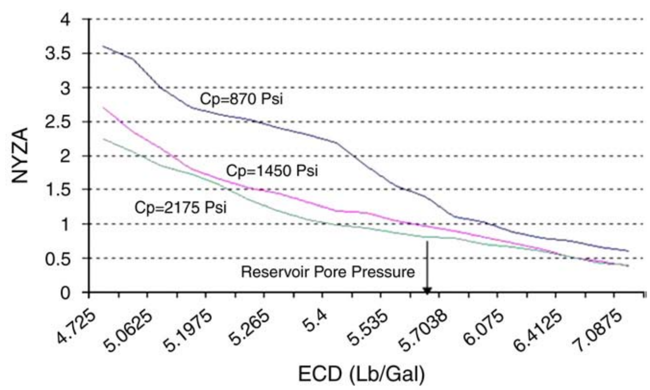

Fig. 7. NYZA versus ECD in field B.

these fields were generated through a finite-explicit code (FLAC) and a finite-element code (Abaqus). Results from both simulators are in a very close match.

7. Finite-explicit simulations

As shown in Fig. 4, FLAC was used for determination of yielded zone area (FLAC, Version 5). The magnitude of maximum displacement vector should always be considered in the acceptable range. Fig. 5 illustrates the typical FLAC output of the displacement vectors.

More than hundred simulations with different ECD values were conducted; Figs. 6 and 7 shows the trend of NYZA changes with different ECDs in field A and B.

As shown in the figures with increasing ECD, the NYZA will decrease and we will have more stable wellbore. Typically, drilling with a bottomhole pressure above than formation pore pressure will decrease the risk of borehole instability due to less yielding area of the rock adjacent to the borehole.

The plots for both fields indicates that there is relatively small amount of yielding (NYZA less than 1.0) predicted for pressures less than reservoir pore pressures. For instance, in field A, ECD ranges from 5.30–5.57 lb/Gal considering the UBD condition would be acceptable. In

Table 5
ECD range for UBD condition regarding different cohesion values.

Cohesion at peak strength (C_p, psi)	ECD range (lb/Gal) considering UBD condition
2175	5.4–5.7
1450	5.67–5.7
870	N/A

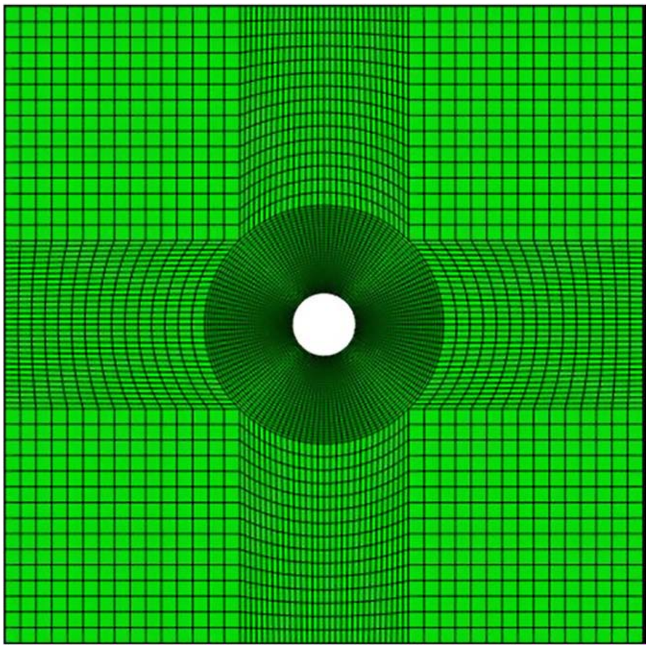

Fig. 8. Two dimensional mesh used for finite-element simulations.

the second field with respect to different cohesions, the ECD range is presented in Table 5. In the case of choosing 870 psi for cohesion, there would be no ECD value considering NYZA be less than 1.0. Based on the wellbore stability simulations, adjusting NYZA criteria to 1.2 as a critical value provided adequate hole cleaning be maintained. An ECD range of 5.06–5.30 lb/Gal was recommended for drilling the horizontal sections of the mentioned well in field A. This was 0.27–0.47 lb/Gal less than reservoir pore pressure. This difference was enough to guarantee underbalanced drilling conditions.

For field B 1450 psi was used for cohesion which resulted in a recommended ECD range of 5.40–5.48 lb/Gal.

8. Finite-element simulations

The mesh was generated and discretized with 2D-Hyper Mesh software and as illustrated in the Fig. 8. For increasing the results accuracy, a very fine mesh was built around the borehole based on using pore pressure elements. A convergence study evaluated the ability of the software to solve various simulations, and satisfactory results were observed with this mesh. The height, width, and length of the model were nearly ten times the wellbore diameter and thus sufficient to eliminate the artifacts in stress distribution that result from end effects. The mesh was then validated based on the Kirsch solution for effective stresses around the wellbore in a pre fractured state. The difference between the results of the numerical model and those of the Kirsch solution proved to be only 0.01%.

After assigning the boundary conditions into the model, a Mohr–Coulomb elasto-plastic material model was used for simulations and the equivalent plastic strain outputs helped us to predict the yielded zone forming around the borehole.

According to uncertainties in the field B input data, results from finite-element simulations in the first field are presented in this paper. Fig. 9 shows the equivalent plastic zone for three cases of pressure difference between pore and wellbore pressure. Using fine mesh for near wellbore region helped us to determine the NYZA factor for all cases that were found to be less than 1.22 that resulting in a very good match to FLAC results. Fig. 10 shows the state of stress around the borehole in one of the cases.

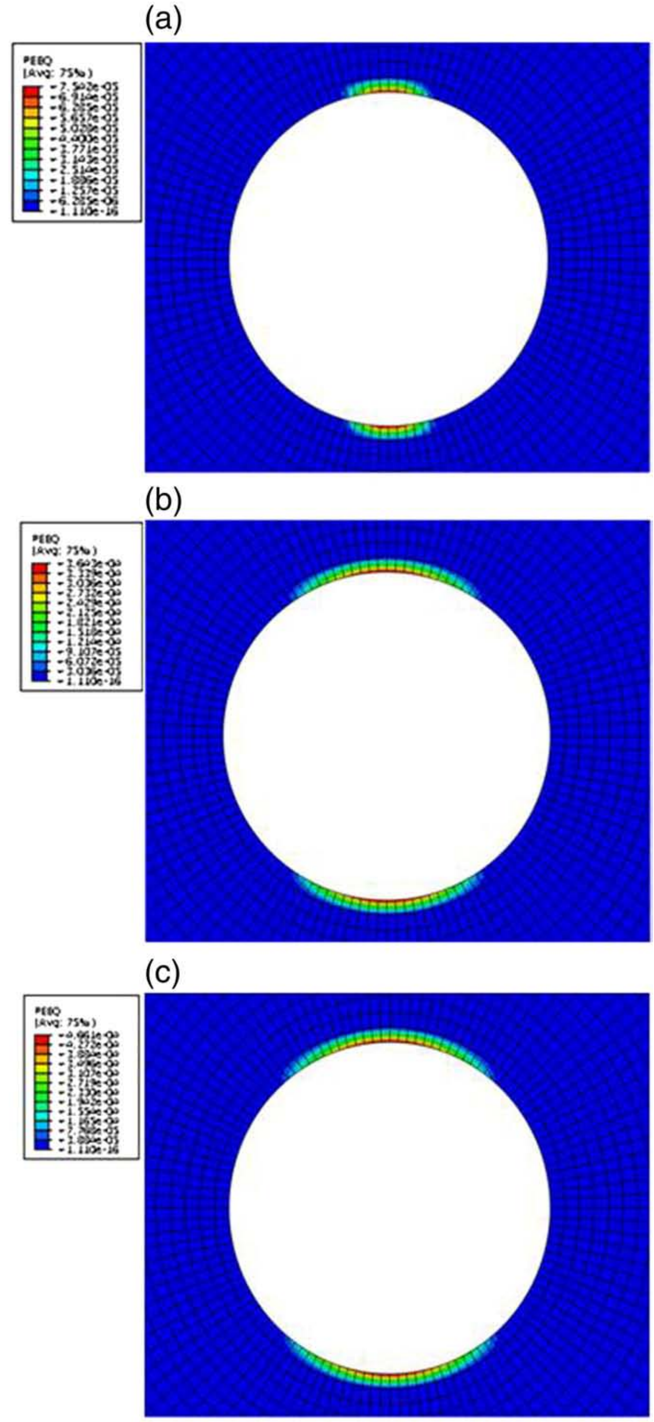

Fig. 9. Yielded zone created from the pressure difference between the wellbore and formation (a) yield zone created for 0.2 (lb/Gal) pressure difference, (b) yielded zone created for 0.3 (lb/Gal) pressure difference (c) yielded zone created for 0.4(lb/Gal) pressure difference.

9. Actual well response

The reservoir section of 61/2 in. wellbore in field A was actually drilled with an ECD of 5.20 lb/Gal so the underbalanced condition was kept most of the time. No sever borehole stability problem was reported during drilling of this section. The daily drilling reports also indicates a decrease of 550% in mud loss compared with the overbalanced condition.

It is not possible to state whether the hole suffered any failure, since no caliper were run in the 61/2 in. hole. No caliper or core data

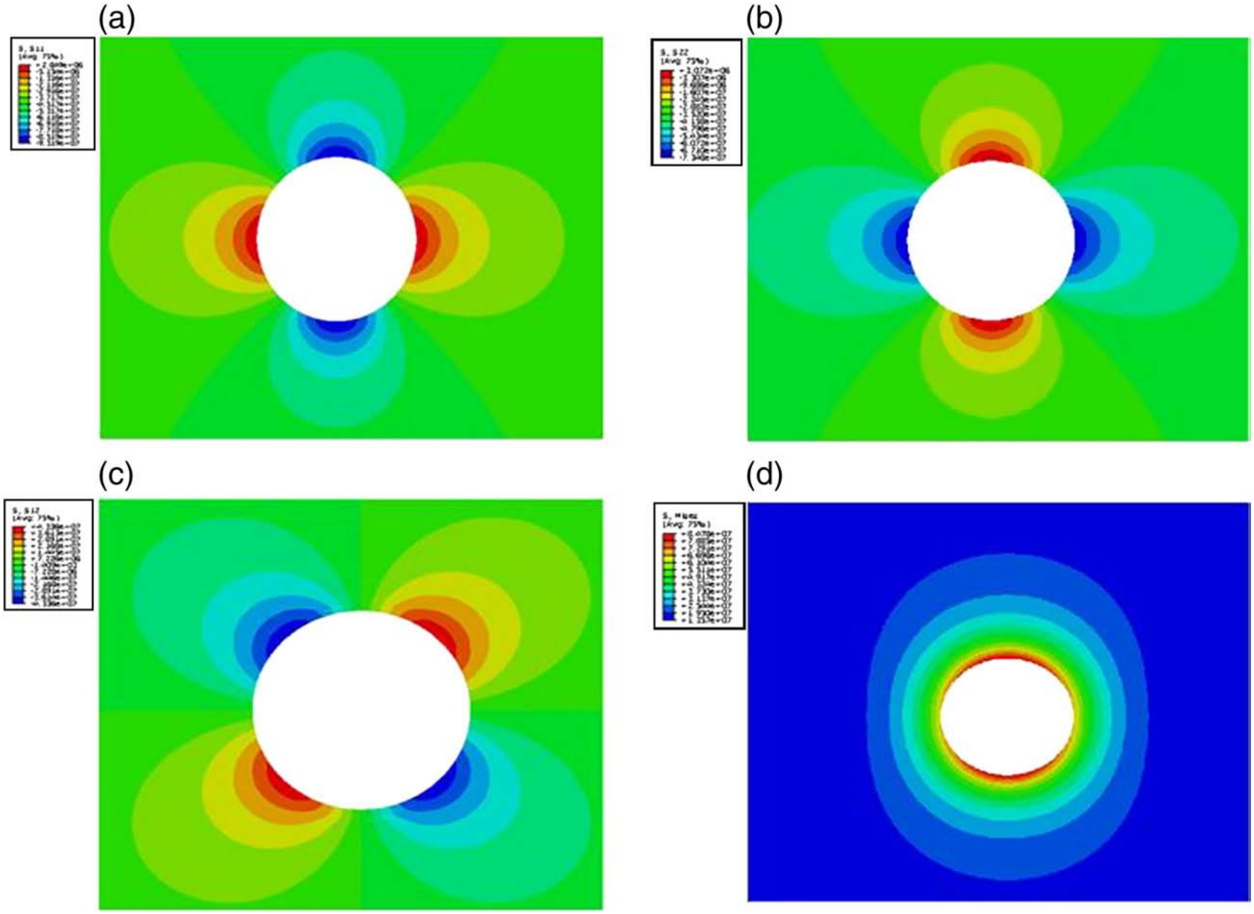

Fig. 10. State of stress around the borehole, (a) Stress in horizontal coordinate, (b) stress in vertical coordinate (c) shear stress around the borehole (d) Von Mises stress around the borehole.

has currently been made available to assess the wellbore stability condition of the well drilled in field B, but the well was drilled without any major complication as in Field A.

10. Conclusions and recommendations

1. Severe lost circulation during overbalanced drilling condition is reported during drilling depleted carbonate fields in Iran, for this reason using the underbalanced drilling technique with proper wellbore stability analysis is recommended for drilling in these fields.
2. An elastoplastic model combined with both Finite-Explicit and Finite-Element codes were used for mechanical wellbore stability analysis of underbalanced drilling technique in depleted Iranian fields. Based on the results and compared with field data using elastoplastic models gives good predictions for wellbore stability in these fields.
3. A criterion based on size of yielded zone or NYZA (Normalized Yielded Zone Area), was used to assess stability condition. Based on the simulation results and for keeping UBD condition in most of the time the critical value of NYZA was adjusted to 1.20 instead of unity in Iranian carbonate fields. Choosing this critical value an ECD of 5.06–5.30 lb/Gal was proposed for drilling the well in field A. Compared with actual field data no wellbore stability problem was encountered during drilling of this well. However, more research and comparisons with field data is necessary to define proper NYZA critical value for stability assessment.
4. The Morales correlation was used for the field B to convert the dynamic values to static. This correlation is for sandstone reservoirs therefore the converted static properties are not necessarily correct to use in carbonate reservoirs as in the case of field B. Due to uncertainties in rock mechanical properties presented in this paper, core data will be required to verify the properties used for field B.
5. For complete wellbore stability analysis in these fields, a combination of both mechanical and chemical effects should be considered. However, only the mechanical effects are considered in this paper.

Nomenclature

C_p	cohesion at peak strength, psi
C_r	cohesion at residual strength, psi
D	depth, m
DST	drill stem test
E	young's modulus, psi
ECD	equivalent circulating density, lb/Gal
g	gravitational acceleration, 9.8 m/s^2
NYZA	Normalized Yielded Zone Area
V_P	compressional velocity, m/s
V_S	shear velocity, m/s
ν_d	dynamic Poisson's ratio
σ_V	overburden stress gradient, psi/ft
$\sigma_{H\max}$	maximum horizontal stress gradient, psi/ft
$\sigma_{H\min}$	minimum horizontal stress gradient, psi/ft
φ_p	friction angle at peak strength, degree
ρ_b	bulk density, kg/m^3
NYZA	Normalized Yielded Zone Area

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The authors would like to thank Mr. P. McLellan for his help on some technical issues used in this paper and NISOC (National Iranian South Oil Company) for their permission to publish the results presented in this paper.

Appendix A. Morales correlation

E_{sta}	$(-2.21 * \mathrm{PIGN} + 0.963) * E_{dyn}$
E_{sta}	Static Young's Modulus
E_{dyn}	Dynamic Young's Modulus
PIGN	log porosity

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