Stress determination and geomechanical stability analysis of an oil well of Iran

AYUB ELYASI^{1,*}, KAMRAN GOSHTASBI¹, OMID SAEIDI² and SEYED RAHMAN TORABI²

¹Faculty of Engineering, Tarbiat Modares University, Tehran 14115143, Iran

²School of Mining Engineering, Shahrood University of Technology, Shahrood 3619995161, Iran

e-mail: a.elyasi1986@yahoo.com

MS received 2 July 2012; revised 24 December 2012; accepted 2 January 2013

Abstract. In this paper, a numerical model using three-dimensional finite difference code FLAC3D is proposed for analysing the stability of an oil well drilled in four formations. Normalized Yielded Zone Area (NYZA, i.e., the ratio of surrounding yielded cross-sectional area to initial area of well) has been determined for different mud pressures. In each formation, by interpolating of obtained NYZA equal to one, the optimized mud pressure was determined using MATLAB software. Practical data including geomechanical parameters along with drilling data from one of Iranian oilfields, Mansouri-54 well have been utilized in this analysis. *In situ* stress was determined using stress polygon method and conducting hydraulic fracturing data in the field. Analytical solution using the Mogi–Coulomb and the Hoek–Brown failure criteria has been carried out and results are compared with the presented model. The results demonstrated that the NYZA and Hoek–Brown criteria might underestimate and overestimate the drilling mud pressure, respectively, and should be used cautiously. In the inclined section of the well, plastic zone showed more extension in the lower part than upper part of the well because of the high stress concentration.

Keywords. Finite difference; NYZA; optimum mud pressure; stress polygon; failure criterion.

1. Introduction

Well stability is one of the crucial issues in oil and gas industries. The issues related to instability of wells, impose significant unwanted costs on drilling operation. Furthermore, it has a deteriorating effect on the time schedule of the project. Hence, in many oil companies well stability analysis is one of the major activities in the well design stage (Detournay & Chen 2005). The key point to conduct a stability analysis of a well is to determine *in situ* stress that surrounded the well

*For correspondence

(Willson *et al* 1999). To determine the *in situ* stress, Zoback *et al* (2003) and Brudy *et al* (1997) for the first time performed a comprehensive project using an integrated stress measurement strategy (ISMS). In the same fashion, Reynolds *et al* (2006) tried to constrain the *in situ* stress at Cooper–Eromanga basin in Australia. They concluded that the *in situ* stress is the direct outcome of complex interactions between tectonic stresses and convergent plates.

The most important condition for stability of a well is to keep a balance between the *in situ* stress in the well wall and the surrounding rock mass strength. In general, the instability in the well is the reaction of surrounding rock mass against induced stresses because of drilling operation. If the strength of rock mass is more than the induced stresses, the well would be stable, otherwise the surrounding rock mass would yield and enhance the probability of over break in the well (Garrouch & Ebrahim 2001).

This paper comprises two scenarios; firstly, *in situ* stresses including vertical, maximum and minimum horizontal stresses are determined in the case study. Then, a numerical model is proposed to analyse the stability of the well based on practical data. The criteria for assessing the well instability, is based on the development of yielded (plastic) area. The criterion, often used for indication of well instability risk is the Normalized Yielded Zone Area (NYZA), which can be obtained by dividing the cross-sectional area of plastic zone to the original area of the well. From the literature it was shown that the instability often occurs when the amount of NYZA is more than one (Salehi & Hareland 2010).

2. Geological background of studied area

The Zagros fold-thrust belt stretches around 2000 km from south-eastern Turkey through northern Syria and Iraq to western and southern Iran (Alavi 2004). Structurally, the Zagros basin is placed in the north of the Arabian plate. Studied formations of the well include Pabdeh, Gurpi, Ilam and Sarvak. The Zagros basin is part of the Tethys Ocean and is one of the most important petroleum reservoirs in the world (Alavi 1994).

The geological history of this basin includes a long time subsidence and deposition which is interrupted by a short-term uplift. Its folding process began during Miocene and Pliocene anticlines and continued until now, hence forming a long anticline (Mottiei 1995). These anticlines constitute most of oil traps in this basin. Mansouri oilfield is located in the northern Dezful subsidence at 60 Km to the south of Ahvaz. It is surrounded by the Ahvaz field from northwest, Abteimoor field from west and Shadegan field from northeast. At oil–water contact surface, the Mansouri field has 39 Km length and 3.5 Km width.

2.1 Lithology of studied formations

Alavi (2004) studied the lithostratigraphic units of the Zagros thrust belt and published the description of its formations. The summary of studied formations is mentioned below:

Bakhtiari (Upper Miocene–Pliocene, 0–800 m): It mainly consists of conglomerate, sandstone, claystone and siltstone. Formation has steep to overturned beds in some parts, and synclines preserve growthstrata of Neogene – Pliocene age.

Aghajari (Upper Miocene, 800–2900 m): The lithofacies of the Aghajari Formation (mudstone, sandstone and conglomerate) were due to a variety of fluvial environments (meandering and braided river channels, inter-channels and bars). The Aghajari sandstones consists of monocrystalline quartz grains showing strong undulatory extinction and crypto-polycrystalline quartz grains, both suggestive of metamorphic source rocks.

Pabdeh (Upper Paleocene to lowermost Oligocene, 2902–3160 m): Thin-bedded Globigerina-bearing deep-marine hemi pelagic–pelagic calcareous shale, marl, and limemudstone with subordinate argillaceous limestone containing fish fossils; foredeepfacies grading toward the northeast into sandy Shabbazan dolomitic limestone and toward the southwest into Sabkha-type Jahrum carbonates (figure 1).

Gurpi (Upper Cretaceous Santonian to Maastrichtian, 3160–3414 m): Dark bluish gray, thin-bedded, deep-marine, Globigerina-bearing pelagic marl (and marly limestone) and hemipelagic claystone; foredeepfacies (resting unconformably on Sarvak and overlapping Ilam) resulting from prograde southwestward migration of proforeland zones (figure 1).

Ilam (Oligocene to lowermost Miocene, 3414–3630 m): Medium to thick-bedded, locally shelly or oolitic, nummulites-bearing limestones (grainstone, packstone, wackestone) shoaling upward above a thin basal conglomerate from fine-grained (low-energy) deep-marine marly limestone to high-energy shallow-marine skeletal grainstone; composed of a number of sequences; unconformity-bounded, highly prolific reservoir; interpreted as transgressive–regressive foredeepfacies of the proforeland basin (figure 1).

Sarvak (Cretaceous, 3630–3768 m): The formation is a thick carbonated unit that was deposited in ‘Neotethys southern margin of Zagros’ area. It is one of the most important hydrocarbon resources production horizons in Iran. Laboratory and field observation lead to recognition of four facies environments: open marine, shale, and lagoon in coastal area of Fars, Khuzestan and Lurestan. The lower lithostratigraphic limit of Sarvak Formation, which is conformable and gradational, overlies the Kazhdumi Formation in section. Upper lithostratigraphic limit of that is secant with Gurpi Formation (figure 1).

3. *In situ* stresses orientation and magnitude in Mansouri-54 well

So far as the depth of oil and gas exploration is concerned, the *in situ* stress orientations manifested by a number of phenomena. These include fault activity, borehole breakout, core discing, center line fracturing in cores, drilling-induced fractures and natural and induced earthquakes (Bell 1996). Breakouts and drilling-induced fractures are the most commonly encountered phenomena (Bell 2003).

In this case, well breakouts are illustrated using Ultrasonic Televiewer Imager (UBI) log which have been obtained from 3650 to 3695 m depth of the well. Figure 2 highlights different instability phenomena in the well. As shown, the well breakouts appear as dark bands of low reflectance on opposite sides of the well at the depth interval of XX1–XX3 and XX28–XX31 in figures 2(a) and (b), respectively. According to observed breakouts at the Mansouri-54 well, it can be inferred that azimuth of S_h is about $(N135 \pm 10S)$, with orientation of NE–SW direction. Since failure and collapse would lead to the high circumferential stress, the best direction of drilling in order to minimize circumferential stress is S_H direction (NE–SW).

In flat terrain the vertical stress at a proposed depth can be assumed integrating the material densities from surface to depth i.e.,

$$S_V = \rho_w g z_w + \int_0^z \rho_b(z) g dz, \quad (1)$$

where, $\rho_b(z)$ and ρ_w are the rock and water densities, respectively. In offshore areas, to calculate the vertical stress, the water depth (z_w) needs to be considered. In the current research, the

Figure 1. Mesozoic–Cenozoic stratigraphy correlation chart of the Zagros basin (Mottiei 1995).

Figure 2. Appearance of breakouts on UBI in Mansouri-54 well which shows minimum horizontal stress direction (a) Depth: 3660–3678; (b) Depth: 3679–3690.

pore pressure is based on hydrostatic pore pressure. Since no information on Equivalent Circulating Densities (ECD) exists for the well, static mud weights have been used to calculate S_H . It is observed that due to the circulation of the drilling mud, the equivalent circulating densities are larger than static mud weights. However, the static mud weights may over-estimate the magnitude of the horizontal stresses.

In this well, the static mud weight was determined to be equal to 69 pcf (1105 kg/m³) for the Pabdeh, Gurpi and Ilam formations and 76 pcf (1216 kg/m³) for the Sarvak formation. Based on its density logs, the average rock density of this particular well is about 2.55 gr/cm³.

Minimum horizontal stress, S_h magnitude in petroleum basins is commonly determined using hydraulic fracture (HF) and leak-off tests (LoTs). To determine *in situ* stresses, many theoretical and practical methods have been presented by researchers (Terzaghi & Richart 1952; Brown &

Hoek 1978; Sheorey 1994). However, most of the proposed methods are in the field of mining and civil engineering and are not applicable in the field of deep underground drillings. The first method by Terzaghi and Richart based on the Poisson's ratio was abolished although it was widely used in the early time. The relations by Hoek – Brown with their upper and lower bonds covered wide ranges of stresses which they had more limitations. Sheorey's model based on deformation modulus has more application in sedimentary rocks but requires the exact knowledge of deformation modulus in two anisotropic directions i.e., E_h and E_v deformation modulus in horizontal and vertical directions, respectively.

Fjaer *et al* (2008) used experimental equations to determine S_h . They used hydraulic fracturing data from whole regions in US Gulf Coast, and derived relationships between horizontal stress and depth. To determine S_h , Breckels and Van Eekelen presented the following relations (Fjaer *et al* 2008):

$$S_h = 0.0053H^{1.145} + 0.46(P_f - P_{fn}) \text{ If } H < 3500, \quad (2)$$

$$S_h = 0.0264H - 31.7 + 0.46(P_f - P_{fn}) \text{ If } H > 3500, \quad (3)$$

where S_h is the minimum horizontal stress in MPa, H is the depth of interest in meters, P_{fn} is the hydrostatic pore pressure in MPa and P_f is the formation pore pressure from the Repeat Formation Test (RFT) in MPa. In the studied well, the obtained data by Leak-off tests and mud losses due to fracturing in several sections reported by the contractor (NIOC 2005) had a good correlation with Eqs. (2 and 3) which they utilized to determine *in situ* stresses. The pore pressure formation was obtained through the RFT in the Mansouri-54 well which is $P_f = 32.6$ MPa in the Pabdeh, Gurpi and Ilam and $P_f = 41.5$ MPa in the Sarvak formations. The RFT Repeat Formation Tester tool has been used to measure formation fluid during the process. Pretest chambers were used to indicate the permeability and to check for seal failures. During pre-test, two small volume chambers opened producing pressure drawdowns. Knowing the amount of drawdown for each chamber, two estimates of permeability were obtained. Once the pre-test chambers were filled, formation permeability could also be calculated from the subsequent buildup to formation pressure (NIOC 2005).

Maximum horizontal stress S_h can be estimated based on the methodology presented by Barton *et al* (1988). They used breakout width and rock strength to calculate S_h . As such, by integrating this methodology to the stress polygon S_h can be obtained. The stress polygon is based on the Anderson's faulting theory and Coulomb frictional theory. Whereas observed fractures on UBI (figure 2) were breakout or compressional fractures, then the S_h is constrained in stress polygon by applying uniaxial compressive strength values in these formations. Figures (3) and (4) show constraining of S_h in stress polygon at the Pabdeh and Sarvak formations. As S_h was obtained in previous section, the stress polygon can be obtained here by drawing the vertical dashed line from S_h axis and constraining the S_h using horizontal dashed line. The above procedure can be repeated for other formations as well.

Based on aforementioned methods, the three *in situ* stresses and pore pressure have been calculated and presented in table 1 for all studied formations.

4. Stability analysis using numerical modelling and Mogi–Coulomb criterion

4.1 Hoek–Brown failure criterion

Hoek & Brown (1980) introduced their failure criterion to facilitate the design of underground excavations in hard rock. The criterion was derived from the results of research into the brittle

Figure 3. Stress polygon which describes magnitude of S_H in the Pabdeh formation at 3012 m.

failure of intact rock by Hoek (1968) and the studies of jointed rock mass behaviour by Brown (1970). The Hoek–Brown failure criterion for rock masses is widely accepted and has been applied in a large number of projects around the world. While, in general, it has been found to be satisfactory, there are some uncertainties and inaccuracies that have made the criterion inconvenient to apply and to incorporate into numerical models and limit equilibrium programs. In particular, the difficulty of finding an acceptable equivalent friction angle and cohesive strength

Figure 4. Stress polygon which describes magnitude of S_H in the Sarvak formation at 3485 m.

Table 1. *In situ* stresses and pore pressure in Mansouri-54 at related formations.

Formation	Depth (m)	P_p (MPa)	σ_v (MPa)	σ_H (MPa)	σ_h (MPa)
Pabdeh	3012	30	76	65	64
Gurpi	3209	32	81	72	69
Ilam	3377	33	84	80	73
Sarvak	3485	34.5	87.5	82	78

for a given rock mass has been a problem since the publication of the criterion (Hoek *et al* 2002). It is noticeable that, most of the criteria like Drucker–Prager and Mohr–Coulomb in Soil mechanics are yield criteria but Hoek–Brown is an empirical fracture criterion.

The Hoek–Brown criterion is defined as

$$\sigma'_1 = \sigma'_3 + \sqrt{m\sigma_c\sigma'_3 + s\sigma_c^2}, \quad (4)$$

where the prime sign of the principal stresses, σ'_1 and σ'_3 represents the effective stresses i.e., ($\sigma'_1 = \sigma_1 - P_0$) and m and s are rock constants.

4.2 Mogi–Coulomb failure criterion

Most of the failure criteria used in rock mechanics were developed before the role of the intermediate principal stress was known. As the real influence of the intermediate principal stress is relatively small (compared to the significance of the other two) such criteria are still valuable approximations, and still are used. For polyaxial stress state, Mogi concluded that the mean normal stress that opposes the creation of the fracture plane is, $\sigma_{m,2}$ rather than the octahedral normal stress, σ_{oct} as the fracture plane strikes in the σ_2 direction.

Al-Ajmi & Zimmerman (2005a) performed ‘polyaxial’ and ‘triaxial’ tests on different rocks. They simplified nonlinear Mogi criterion and defined linear Mogi criterion that known as ‘Mogi–Coulomb’. Mogi–Coulomb criterion in $(\tau_{oct} - \sigma_{m,2})$ space is given by

$$\begin{aligned} \tau_{oct} &= a + b\sigma_{m,2}, \\ \sigma_{m,2} &= \frac{\sigma_2 + \sigma_3}{2}, \\ a &= \frac{2\sqrt{2}}{3}c \cos \phi, \quad b = \frac{2\sqrt{2}}{3} \sin \phi, \end{aligned} \quad (5)$$

where τ_{oct} is the octahedral shear stress, $\sigma_{m,2}$ is the mean normal stress, a and b are constants. The first and second stress invariants, I_1 and I_2 , are defined by

$$I_1 = \sigma_1 + \sigma_2 + \sigma_3, \quad I_2 = \sigma_1\sigma_2 + \sigma_1\sigma_3 + \sigma_2\sigma_3. \quad (6)$$

In addition, utilizing the effective stress concept, the Mogi–Coulomb criterion can be expressed as

$$(I_1^2 - 3I_2)^{1/2} = a' + b'(I_1 - \sigma_2 - 2P_0), \quad (7)$$

where

$$a' = 2c \cos \phi, \quad b' = \sin \phi. \quad (8)$$

Table 2. Rock mass physic-mechanical properties of Mansouri-54 related formations.

Formation	Properties						
	E_s (GPa)	E_d (GPa)	Average density (Kg/m ³)	UCS (MPa)	ν	C (MPa)	ϕ (deg.)
Pabdeh	4	8.4	2550	50	0.25	2	33
Gurpi	4.5	6.8	2550	50	0.25	3	31
Ilam	5	8.3	2550	55	0.25	3	33
Sarvak	8.5	12.5	2550	60	0.25	4	35

*Note: E_s : Static Young's modulus, E_d : Dynamic Young's modulus, UCS: Uniaxial Compressive Strength, ν : Poisson's ratio, C: Cohesion strength, ϕ : Friction degree

Mansouri-54 well stability analysis was carried out in four related formation type i.e., Pabdeh, Gurpi, Ilam and Sarvak because of different properties of each formation. In Sarvak formation, the well is inclined with an inclination of 39° and an azimuth of 25° (with respect to the North), but in other three formation, the well is vertical. Physico-mechanical properties of the formation are presented in table 2. Constant parameters m and s in Hoek–Brown failure criterion are calculated using RocData software (Rocscience 2004) and the resulted values are 4.99 and 0.88, respectively.

4.3 Numerical modelling

In this study, the FLAC3D numerical code which is based on the finite difference method is utilized in order to analyse the stability of wells (ITASCA 2006). The dimensions of the generated models are 400 × 200 × 200 cm. The modelled wells are 42 cm in diameter. It was obtained that, in all formations by increasing the mud pressure displacements and plastic zone reduces.

Figure 5 illustrates the plastic zones surrounding the vertical well in different mud pressures in Mansouri-54 well located in Ilam formation. It can be observed that by increasing mud pressure in this case, the radius of plastic zone decreases. In this figure, the zones which are indicated by blue colour are in elastic state otherwise they are in plastic state.

The optimum mud pressure (the minimum mud pressure needed for well stability) is the pressure in which the NYZA is equal to one. Therefore, in each model the variation of NYZA in different mud pressures are calculated and then the best curve is fitted to the resulted points employing MATLAB software. As a result, the optimum mud pressure is accurately determined using the curve formula. For example, in figure 6 the variation of NYZA versus overbalance mud pressure (mud pressure–pore pressure) is illustrated for Mansouri-54 well in all four formations. It can be seen that, with the increase in mud pressure, the NYZA reduces and therefore the well gets more stable. At the beginning, the NYZA decreases with a high rate but gradually lower rate of reduction is seen.

The calculated mud pressures using the Mogi–Coulomb, NYZA and Hoek–Brown criteria are presented in table 3. The results show that the mud pressures calculated from NYZA method are less than the Mogi–Coulomb and Hoek–Brown mud pressures. The lower mud pressures obtained from the NYZA method with respect to the Mogi–Coulomb criterion is because the NYZA method does not consider the elastic deformations.

It is known that the Mogi–Coulomb criterion can accurately estimate the failure of varied rock masses (Al-Ajmi & Zimmerman 2005b). Hence, it can be concluded that the NYZA method

Figure 5. Plastic zone surrounding Mansouri-54 well located in Ilam formation in a variety of mud pressures.

Figure 6. Variation of NYZA for Mansouri-54 well versus the mud pressure in four related formations.

may underestimate the mud pressure needed for well drilling and should be used cautiously. Also the mud pressure was overestimated by using the Hoek–Brown criterion. Therefore, it can be seen that optimum mud pressure can be predicted by using the Mogi–Coulomb failure criterion because it considers true-triaxial state of stresses in the calculations. The Mansouri-54 mud pressure in Sarvak formation despite its much greater depth and more *in situ* stresses is the least among all formations and the main reason is higher cohesion of this formation with respect to other three formations.

The obtained optimum mud pressures that lead to the stability of the well from table 3 have been applied in the numerical models. The models have rerun and the plots of plastic zones ($NYZA = 1$) around the inclined and vertical wells are shown in figure 7 for all formations. It can be seen that, the plastic zone around inclined well (figure 7d) have asymmetrically oval-shaped because of the effects of transformed *in situ* stresses. In the lower part of the well, plastic zone extension is more than the upper part because of the much stress concentration. It should be noticed that the elliptic shape of the inclined well in figure 7d is because of projection of the well cross-section on vertical plane.

Table 3. Overbalance mud pressures obtained by means of NYZA, the Mogi–Coulomb and the Hoek–Brown criteria in Mansouri-54 well at four related formations.

Formation	Overbalance mud pressures (MPa)		
	NYZA	Mogi–Coulomb	Hoek–Brown
Pabdeh	9.51	12.1	15.2
Gurpi	10.44	14.3	16.7
Ilam	11.52	15.9	18.4
Sarvak	9.49	11.8	14.4

Figure 7. Plastic zone surrounding Mansouri-54 well located in optimum mud pressures ($NYZA = 1$).

5. Conclusions

This paper presents a numerical modelling for the stability analysis of the Mansouri-54 well. The results compared with analytical solution by the Mogi–Coulomb and Hoek–Brown failure criteria. The input data for this analysis including *in situ* stresses and geomechanical parameters were based on practical information. *In situ* stresses were determined in all formations using stress

polygon and hydraulic fracturing data of the studied field. Numerical modelling has been conducted with FLAC3D software. In numerical simulation normalized Yielded Zone Area (NYZA) has been obtained for different mud pressures. Analytical solution using the Mogi–Coulomb and Hoek–Brown criteria has been carried out and their results were compared with the present model. The results demonstrated that the NYZA method may underestimate the drilling mud pressure and should be used thoughtfully. Also, using the Hoek–Brown criterion mud pressure was overestimated. Consequently, it can be understood that optimum mud pressure can be predicted by using the Mogi–Coulomb failure criterion because it takes into account true-triaxial state of stresses in the calculations. It was concluded that with increasing mud pressure until optimum amount the extension of plastic zone around the well would decrease. In the Mansouri-54 well, mud pressure in Sarvak formation despite its much greater depth and more *in situ* stresses is less and the main reason is higher cohesion of this formation with respect to other three formations. In the inclined section of the well, plastic zone showed more extension in the lower part than upper part of the well because of the much stress concentration.

References

- Al-Ajmi A M and Zimmerman R W 2005a Relation between the Mogi and the Coulomb failure criteria. *Int. J. Rock. Mech. Min. Sci.* 42: 431–439
- Al-Ajmi A M and Zimmerman R W 2005b Relationship between the parameters of the Mogi and Coulomb failure criterion. *Int. J. Rock. Mech. Min. Sci.* 42(3): 431–39
- Alavi M 2004 Regional stratigraphy of the Zagorsk fold-thrust belt of Iran and its proforeland evolution. *Am. J. Sci.* 304: 1–20
- Alavi M 1994 Tectonics of the Zagros orogenic belt of Iran: new data and interpretations. *Tectonophysics* 229: 211–238
- Barton C A, Zoback M D and Burns K L 1988 In-situ stress orientation and magnitude at the Fenton geothermal site, New Mexico, determined from well breakouts. *Geophys. Res. Lett.* 15(5): 467–70
- Bell J S 1996 In-situ stresses in sedimentary rocks (Part 1) Measurement techniques. *Geoscience Canada* 23(2): 85–100
- Bell J S 2003 Practical methods for estimating in-situ stresses for borehole stability applications in sedimentary basins. *J. Pet. Sci. Eng.* 38: 111–119
- Brown E T 1970 Strength of models of rock with intermittent joints. *J. Soil Mech. Foundn. Div. ASCE* 96, SM6, 1935–1949
- Brown E T and Hoek E 1978 Trends in relationships between measured rock in situ stresses and depth. *Int. J. Rock. Mech. Min. Sci. & Geomech. Abstr.* 15: 211–215
- Brudy M *et al* 1997 Estimation of the complete stress tensor to 8 km depth in the KTB scientific drill holes; implications for crustal strength. *JGR102-8* 18: 453–75
- Detournay C and Chen X 2005 Factors governing mud filtration and impact on well stability: *40th U. S. Symp. Rock Mech.* USRMS
- Fjaer E *et al* 2008 *Petroleum related rock mechanics*. 2nd ed. UK, Elsevier
- Garrouch A A and Ebrahim A S 2001 Assessment of the stability of inclined wells. *Pet. Eng. Dep.* Kuwait Univ. SPE 68861
- Hoek E 1968 Brittle failure of rock. *In Rock Mechanics in Engineering Practice*. Stagg K G and Zienkiewicz O C (eds), 99–124
- Hoek E and Brown E T 1980 *Underground Excavations in Rock*. London; Instn Min; Metall
- Hoek E, Torres C C and Corkum B 2002 Hoek–Brown failure criterion. *Proc. NARMS-TAC Conference*, Toronto, 1: 267–273
- ITASCA FLAC3D 2006 Student License. *Itasca Consulting Group*, Inc. USA
- Mottiei H 1995 Geology of Iran; Petroleum Geology of Zagros. *Geological Society of Iran Publication* 37(2): 1009 P

- National Iranian Oil Company (Southern branch), 2005 Geological studies office, Report of DSI measurements in Mansouri oil field, Ahvaz, Iran
- Reynolds *et al* 2006 Constraining stress magnitudes using petroleum exploration data in the Cooper-Eromanga Basins. *Australia Tectonophysics* 415: 123–140
- Rocscience Inc. 2004 *Roc Data 3.0 User Guide*
- Salehi S and Hareland G 2010 Numerical simulations of well stability in under-balanced-drilling wells. *J. Pet. Sci. Eng.* S 0920-4105(10): 00078-1
- Sheorey P R 1994 A theory for in situ stresses in Isotropic and transversely isotropic rock. *Int. J. Rock. Mech. Min. Sci. & Geomech. Abstr.* 31(1): 23–34
- Terzaghi K and Richart F E 1952 Stresses in rock about cavities. *Geotechnique* 3: 57–90
- Willson S M *et al* 1999 Drilling in South America: A well stability approach for complex geologic conditions. *SPE 53940. In: Sixth LACPEC Conference*. Caracas, Venezuela
- Zoback M D *et al* 2003 Determination of stress orientation and magnitude in deep wells. *Int. J. Rock. Mech. Min. Sci.* 40: 1049–1076