Stability Analysis of a Horizontal Gas Well in a Strike-Slip Fault Regime

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Abstract:

Fault regimes have significant effects on oil and gas wells' stability. Although vertical wells have different geo-mechanical behaviors, horizontal wells have more critical conditions when they will be encountered with fault regimes changes. In this case, a horizontal gas well in a specific depth in the South Pars gas field is considered in the strike-slip fault regime with the poroelastic state of the rock mass and anisotropic horizontal stresses which is analyzed with the Finite Element Method by the ABAQUS software. This analysis is processed statically in a certain time period (the total time of geo-static and drilling steps). The well pressure has increased continuously from the formation pore pressure (lower limit of allowable mud pressure window) to fracture pressure limit (tensile failure limit) in the second step of the analysis. The mud pressure optimization has been done based on the stress and plastic strain reduction at the borehole wall.The results showed that, the borehole stability will not be satisfied by the lower limit of well pressure window (formation pressure) or its upper limit and the optimum mud pressure in horizontal gas wells is a little higher than the minimum level of well pressure.

Keyword: Fault regimes, horizontal gas well, pressure optimization, ABAQUS program, stability analysis

1. Introduction

Due to increasing production demands of hydrocarbon reservoirs in the last decades, wells have been more complex from the point of view of effective parameters on their stability, and drilling operations have been more difficult. Not only technical challenges are taking more time to drill, but also any instability on the wellbore could increase the time and cost of the operation significantly [1]. According to the expectations which are estimated from the drilling data, at least 10% of wells' budgets spend on the unexpected events which are related to the instability of wellbores. This 10% is approximately 1 billion dollar annually. Actually, stability issues sources are caused by a combination of interactions between rock and fluid, applied stresses condition, unusual formation behaviors and inappropriate drilling operation [2]. Although rock mechanics research usage has been increasing in well planning and it was improving the drilling operations, majority of the actions and decisions in this area are done based on the previous surveys and experiences. Despite so many efforts which have done in these years, difficulties related to the instability of the wells are still happening for the companies in this area. Usually, wellbore collapse and producing sand are the practical consequences of instability. If the instabilities does not improve and treat effectively, further challenges such as bit failure, wellbore break out , BHA erosion, mud loss, bit changing and directional drilling will need surely [5, 14]. Fault regimes and specifically reverse fault and strike-slip fault regime have significant effects on the vertical wells instability and specially horizontals. In this case, the strike-slip fault regimes' influences on the stability of horizontal gas well in the South Pars gas field will be analyzed and the mud pressure optimization will be performed in the allowed (standard) mud pressure window.

Due to the well length which is much longer than the diameter, it is not possible to survey a whole model from surface to the specific depth, because well will be assumed as a line in majority of the numerical software. Moreover, the analysis time will be increasing and also surveys and results of the simulation will not be feasible. Thus, 3D finite model are provided to analyze the well stability in separated periods, which well instability may be occurred by the rock lithology or pore pressure or drilling factors such as mud type and mud weight [6, 16].

In this research, Mohr Coulomb failure criterion has been used for analyzing the horizontal well stability. The fault regime was strike-slip and the allowed mud pressure has been assumed between formation pore pressure and tensile failure limit (fracture pressure) in the specific depth. This analysis is performed with well-stablished method and has been done in ABAQUS finite element software. According to the FMI logs (electrical logs) in this field, the maximum horizontal stress direction is along North East-South West trend and the minimum horizontal stress direction is along North West-South East trend and it is also perpendicular to the maximum horizontal stress direction. Stability analysis of a horizontal gas well is performed both along the maximum horizontal stress (azimuth angel=0º) and minimum horizontal stress (azimuth angel=90º) with anisotropic state of horizontal stresses in the formation [8, 17, 19]. Wellbore stability optimization is done based on the well pressure (bottom hole fluid pressure) and the borehole directions along minimum horizontal stress or maximum horizontal stress at the depth of 2991m in the Kangan formation (K_2) situated in the South Pars gas field. The gas well stability analysis in Kangan formation has been done on the vertical well also, and in all cases, the borehole stability was satisfied by minimum mud pressure (formation pressure) in the vertical well. Due to the sensitivity of the horizontal wells, stability analysis will be performed specifically for the horizontal well in this case. The probability of a gas well instability is higher than an oil well, because of gas critical flow through the bore wall and its low specific weight which makes a critical condition relevant to borehole instability and gas kick. Thus the stability analysis in gas wells in comparison to the oil wells is so vital and necessary operation.

2. South Pars gas field

South Pars gas field is the largest gas field in the whole world and situated in Middle East, Persian Gulf of Iran. It contains a huge volume of gas in place about 500 trillion cubic foot in its gas reservoirs. Dalan and Kangan formation are the gas reservoirs in this field which are related to the geologic periods of Permian and Triassic.

3. Finite element simulation

Finite element method is one of the solutions for the differential equations for one specific object or specific structure under the physical conditions. In this method, object, area or structure divides into one, two or three dimension parts. Each of these separated parts is named as a finite element. This method is based on the continuum modeling and the elements' boundary points are called as a node [3, 4].

The horizontal gas Well model is assumed as a cubic block with $6 \times 2.376 \times 2.376 m^3$ dimensions. The inner well diameter is considered 8.5 inches which is equal to 0.216m. It is tried to simulate the wellbore near to real wellbore conditions, thus the reservoir rock which surrounds the borehole is assumed with porosity and pore pressure [4, 5, 6, 16, 17]. The vertical stress applied to the upper side of the model in a uniform pressure. Furthermore, the horizontal stress values are applied under the geo-static condition into the ABAQUS program and with the aid of geo-static step, the vertical stress differences from top face of the model to bottom face are also presumed in the model. Wellbore pressure is applied as a radial uniform pressure on the borehole wall. The difference between cubic model boundary and the well boundary is assumed 5 times of the well diameter, thus the in-situ stress condition will be prevailed at the model boundaries. Bottom face of the cubic rock model is restrained along Z axis direction (vertical direction is along the local gravity vector) with displacement-rotation method into the ABAQUS program. The lateral faces normal to the X axis are restrained along the X axis direction and also the lateral faces normal to the Y axis are restrained along the Y axis direction with displacement-rotation method. Boundary conditions related to the pore pressure are considered into the whole model in the first analysis step (geostatic step) and due to radial flow of the fluid, pore pressure boundary condition is considered both into the well and surrounds of the model in the drilling step (applying pressure step) which can show the effects of fluid flow between the borehole and the reservoir (Figure 1) [20].

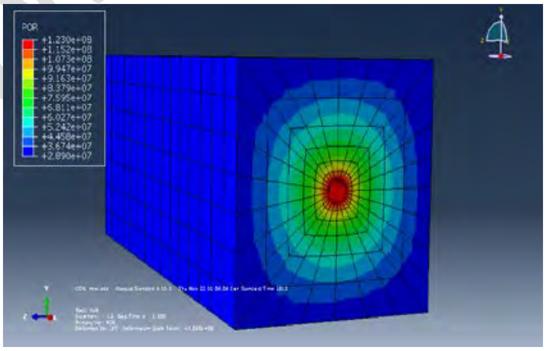

Figure 1: Radial fluid (gas) flow between external boundaries and borehole

This simulation contains two fundamental steps. First is the geo-static step and second one is the drilling step and applying pressure into the well. Required time for each of these steps is 1 second and total time of the static analysis is 2 seconds [6, 7,16].

3.1. Geostatic step

In this step, model condition will be considered before the drilling operation and the system will be balanced and the equilibrium condition also will be satisfied either. The stress, strain, displacement values and pore pressure changes are negligible. In this step, in-situ stress conditions and the gravity force into the rock model will make the simulation near to the reality before the drilling operation. The required time of this step will be 1 second.

3.2. Drilling step and applying well pressure

In this step, due to drilling, stress regime on the wellbore wall will be diversified and the stress, strain and displacement values with pore pressure will be increased near the well. In this step, we try to decrease and optimize the plastic strain, displacement and stress values on the borehole wall as much as possible after drilling by applying mud pressure into the well. Time of this step is from second 1 until second 2.

4. Meshing part

Model meshing technique will be based on the structural and hexagonal method and cubic elements will be provided regularly into the whole model. Figure 2 shows this meshing.

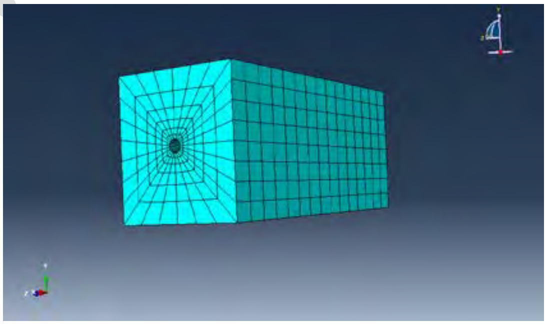

Figure 2: Structured hexagonal meshing

5. Input data for constructing the rock model

In this analysis, Mohr-Coulomb failure criterion is used for simulating the fracture initiation on the wellbore wall and input data for ABAQUSe software are based on this criterion. Input data contain density, Young's modulus (E), dilation angle (ψ), friction angle (ϕ), porosity (n), Poisson's ratio (v), cohesive strength (C) and Biot's factor (α) [1, 2].

6. Rock property parameters

Parameters related to the rock are in the table 1 and 2. These parameters contain physical and mechanical specifications of the rock.

Table 1: Physical and mechanical parameters of the rock

Vertical stress (Mpa)	Hydrostatic pore pressure (Mpa)	Minimum horizontal stress (Mpa)
72.4	38	39.8
Cohesion (Mpa)	Tensile strength (Mpa)	Internal friction angel (degree)
6.53	2.47	43.5

Table 2: Physical and mechanical parameters of the rock

Maximum horizontal stress (Mpa)	Porosity (%)	Biot's factor
77	4.6	0.76
Young's modulus (Gpa)	Density (Kg/m^3)	Poisson's ratio
4.92	2714	0.21

7. Poroelastic model

Deep underground rocks are made up of matrix and non-solid section. Non-solid section contains pores, cracks, fractures and also fluid in the pores [1, 2]. Pore pressure affects distributing stresses effectively [5]. In the majority of the oil and gas fields, pore pressure was one of the most important issues for instability of the wells [6, 15]. Based on the stress distributing equations in elastic and porous elastic modes, which are mentioned in different sources [1, 2] and which is not mentioned in this research, mud pressure analysis will be examined between pore pressure limit (α.Pf) and tensile failure limit (fracture pressure).

8. In-Situ vertical stress estimation

In this case, in-situ vertical stress has been determined by Terzaghi equation [1, 2] and density has been assessed from surface until depth 2991m by gamma-gamma logs. Finally, density has been put in Terzaghi equation to calculate the in-situ vertical stress. Vertical stress in a specific depth of the well is equal to weight of overburden which is located on the top of it [1, 2, 12]. Thus, vertical stress can be calculated by accumulating the stresses which are came from thin elements weights and presented in equation 8-1.

$$S_v = \int_0^z \rho(z) g\, dz \approx \bar{\rho} g z \quad (1)$$

In this equation, ρ(z) is density as a function of depth, g is acceleration of gravity and the second ρis average overburden density.

9. Minimum and maximum horizontal in-situ stresses

Due to lack of mini fracture test, leak-off test and hydraulic fracture data for determination of in-situ stresses, determination of minimum and maximum horizontal stresses based on the strike-slip fault regime in this analysis will be calculated by minimum and maximum horizontal stress of Rummel's equation, 1986 (Eq.(4) and (5)) which are applicable for the depth range between 500m to 3000m [18]. K is the ratio of maximum or minimum horizontal stress to vertical stress (Eq.(2) and (3)).

$$K_{max} = \sigma_{hmax}/\sigma_v \quad (2)$$

$$K_{min} = \sigma_{hmin}/\sigma_v \quad (3)$$

$$K_{max} = 0.98 + 250/z \quad (4)$$

$$K_{min} = 0.5 + 150/z \quad (5)$$

Maximum and minimum values of horizontal stress in strike-slip fault regime have calculated by equations 2 and 3 which are derived from equations (4) and (5). They are presented in table 1.

10. Determination of the fracture pressure (tensile failure limit)

Based on the strike-slip fault regime ($\sigma_{hmax}>\sigma_v>\sigma_{hmin}$), the general formula for calculating fracture pressure (P_{frac}) in vertical wells are as follows.

10.1. With anisotropic horizontal stresses ($\sigma_{hmax}\neq\sigma_{hmin}$):

$$P_{frac}=3\sigma_{hmin}-\sigma_{hmax}-(\alpha\times P_f)+T_0 \quad (6)$$

10.2. With isotropic horizontal stresses

$$P_{frac}=2\sigma_{hmin}-(\alpha\times P_f)+T_0 \quad (7)$$

The general formula for calculating fracture pressure (P_{frac}) in strick-slip fault regime ($\sigma_{hmax}>\sigma_v>\sigma_{hmin}$) for horizontal wells are as follows:

10.3. With anisotropic horizontal stresses ($\sigma_{hmax}\neq\sigma_{hmin}$):

- Along minimum horizontal stress:

$$P_{frac}=3\sigma_v-\sigma_{hmax}-(\alpha\times P_f)+T_0 \quad (8)$$

- Along maximum horizontal stress:

$$P_{frac}=3\sigma_{hmin}-\sigma_v-(\alpha\times P_f)+T_0 \quad (9)$$

P_f is hydrostatic pore pressure and α is Biot's factor.

11. Horizontal gas well stability analysis along the minimum horizontal stress

In this case, a horizontal gas well is along the minimum horizontal stress with 90 degree azimuth angel and is also perpendicular to the North East-South West direction of the maximum horizontal stress. The static analysis results have shown that the difference between maximum horizontal stress and vertical stress which were applied in longitudinal sides of the model is low in this condition, subsequently, stresses on the borehole wall will be in the same values and they will not make any instabilities by producing plastic strains or large stresses on the wellbore wall during applying optimized pressure into the well [10, 15]. In the drilling step, pressure analysis is performed in the allowed mud pressure window by constant increasing of the well pressure between formation pressure and fracture pressure for determination of optimized well pressure window and the most optimized well pressure [15, 21].

Firstly, the well pressure has been increased constantly in the statically limitation time in second 1 to second 2 during the drilling step from formation pore pressure of 29.1 Mega Pascal (with Biot's factor) to the tensile failure limit or fracture pressure of 113 Mega Pascal (Fig. 5). The results have shown that there is no plastic strain firstly in drilling step (Fig. 6); but, it has come when the pressure has increased in the limitation time of 1.502 second and it continues to increase until the end of drilling step (Fig. 6). Figure 6 shows that, applying mud pressure more than 71 Mega Pascal which is equivalent to the 1.502 second of the drilling step time limitation causes plastic strain and yield stress around the bore from 1.502 second (equal to 71 Mega Pascal pressure of the well) to the end and it will make borehole instabilities and it probably makes fractures and the well collapse. The stress analysis on 2 points on the cross section of the horizontal gas well, node number 210 on the vertical edge of the bore cross section and the node number 35 on the lateral edge (Figure 3) showed that the amounts of stresses on the vertical edge of the bore cross section were high (Fig. 7), but then are decreased since 2 nodes diagrams cross each other by applying pressure on the well from formation pore pressure to the fracture pressure in the time limitation of second 1 to second 2 among the drilling step (second 1.24, Figure 4) and after that the node 35 diagram (on the lateral edge) from figure 4 has been increased from second of 1.24 to the end of step because of borehole instabilities. The figure 4 shows the average stresses on the bore cross section (Mises stress) and according to the figure 4, cross point of the vertical edge diagram (node 210) and lateral edge (node 35) in the horizontal gas well is the most optimum well pressure in this analysis (second 1.24, Figure 4, Figure 5) and it showed in the stress and well pressure versus time curve. The time limitation from pore pressure (second 1) to optimized well pressure (second 1.24) is selected in this case as the most optimized mud pressure window (second 1 to 1.24, Figure 5). Node 210 and 35 are shown in figure 3 and the all curves were plotted between second 1 to second 2 of the drilling step and the geostatic step was not mentioned in this analysis due to the lack of any instability in the geostatic step.

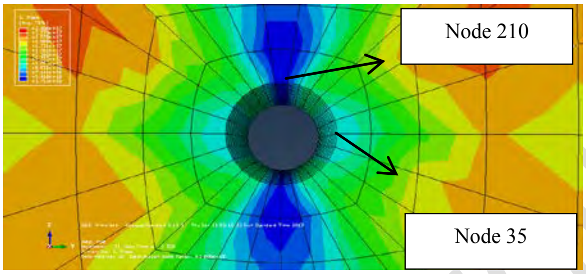

Figure 3: Node number 210 on the vertical edge and the node 35 on the lateral edge

The numeric results in this case are summarized in table 2 and the optimized stress and drilling mud pressure are presented in Mega Pascal unit.

Table 3: The stress on the borehole wall, well pressure and plastic strain

Mud window	Lower limit	Fracture pressure	Optimum value
Time (second)	1	2	1.24
Well pressure (MPa)	29.1	113	45
Bore stress on z axis (MPa)	68	6.8	37
Plastic strain	0	2.8×10^{-2}	0

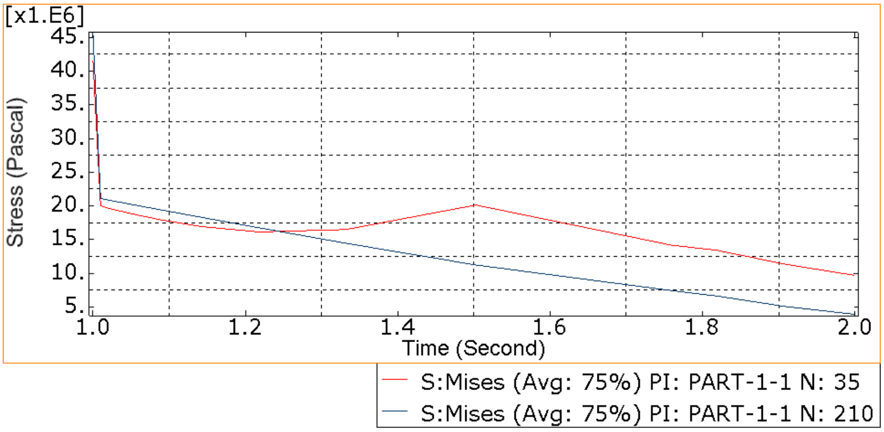

Figure 4: Borehole wall average stress (Pascal) versus time (Second) graph for the node 210 (on vertical edge) and the node 35 (on lateral edge)

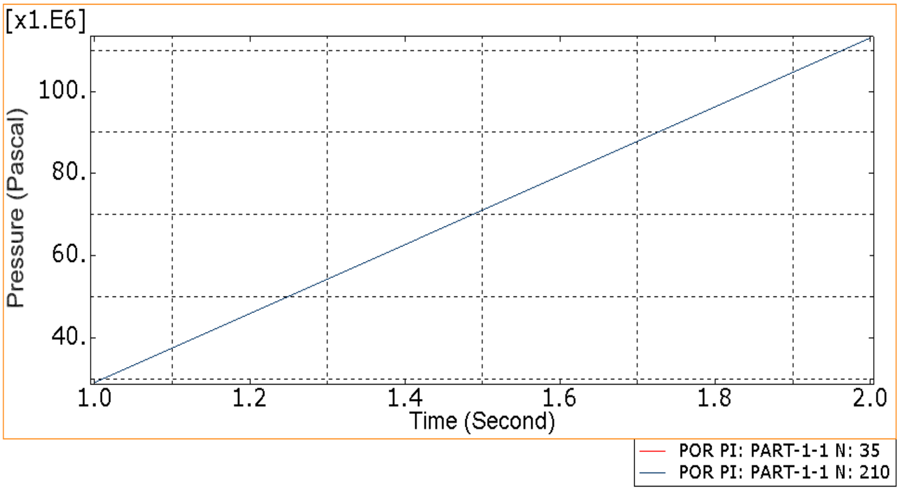

Figure 5: Well pressure (Pascal) versus time (Second) graph

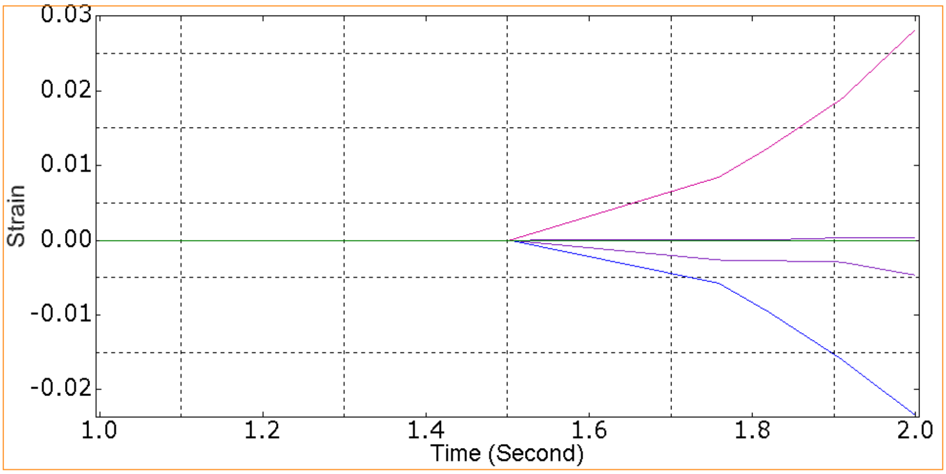

Figure 6: Plastic strain versus time (Second) graph for nodes 210, 35

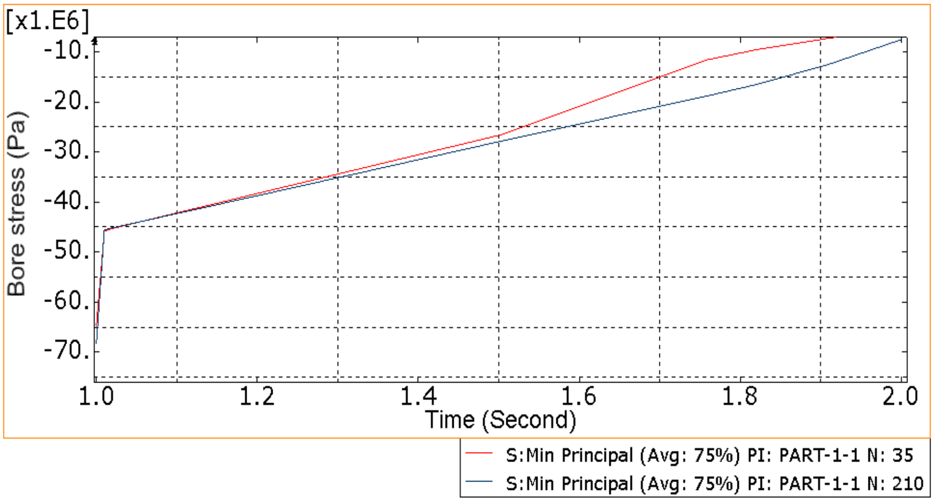

Figure 7: Bore wall compressive stress (Pascal) on Z axis versus time (Second)

12.Horizontal well stability analysis along maximum horizontal stress

The well direction in this case is along maximum horizontal stress in North East-South West direction with zero degree of azimuth angel. The analysis of well pressure in this direction has shown that the tensile failure will be occurred at the well pressure of 20.37 Mega Pascal. The fracture pressure in this direction is lower than the formation pressure of 29.1 Mega Pascal, thus drilling the bore in this direction may cause failure and well collapse and the probability of sand producing will be high [10, 11, 13]. Consequently, stability analysis in this direction has been stopped and the analysis has been processed just in the minimum horizontal stress direction.

13.Results and discussion

- The best direction for drilling a horizontal gas well in formations with anisotropic horizontal stress will be along the minimum horizontal stress, this is because of the lowest instabilities in this direction.
- In this case, the activities of the strike-slip fault regime have made large differences between minimum and maximum horizontal stresses. There is no possibility to drill a well along the maximum horizontal stress. This is because of drilling along this direction causes the pore pressure becomes more than the tensile failure stress or fracture pressure and the wellbore wall will be surely damaged.
- Applying well pressure in the allowed mud pressure window in a horizontal gas well showed that, the borehole stability will not be satisfied by the lower limit of well pressure window (formation pressure) or upper limit of well pressure window. The optimum mud pressure in horizontal gas wells is higher than the minimum level of well pressure.
- By optimization of the horizontal gas well, the wellbore wall stress will be reduced a little by applying mud pressure a little more than the pore pressure level. This pressure has balanced the wellbore wall stresses and the level of plastic strain in well cross section has been reached to zero.
- The mud pressure analysis has demonstrated the optimum pressure and optimum mud pressure window in this depth were determined by calculating the cross point which is gained by crossing the mentioned nodes graphs (on the vertical edge (node 210) and lateral edge (node 35)) in the stress versus time curve.
- By assessing the plastic strain-time graph, the minimum mud pressure which can produce the plastic strain was determined. By knowing this critical pressure in drilling the horizontal gas wells, we never apply the well pressure more than this critical pressure.

- The stability analysis in the static condition has progressed with high accuracy by applying pore pressure, fluid seepage effects and applying mud pressure into the well.
- Based on the continuum state of rock model in this analysis, fractures and joints effects on the wellbore stability can analysis in the future's research by this method.

14.References

- Reference to a book (monograph)

[1] FjaerE., (2008). Petroleum Related Rock Mechanic, Elsevier Publication Books, p. 491.

[2] Zoback M. D. (2007). Reservoir Geomechanics, Cambridge university Press, p. 464.

[3] Sadrnejad S. A., (2009). Introduction to Finite Elements Method, Second Edition.

- R eference to a journal article

[4] Wang X., R.L. Sterling, Stability analysis of a borehole wall during horizontal directional drilling, Tunnelling and Underground Space Technology, Volume 22, Issues 5–6, September–November 2007, Pages 620-632.

[5] Aadony, B.S., (2003). Introduction to special issue on borehole stability. J. of Pet. Sci. Eng. 38, 79-82.

[6]Papamichos E., Analysis of borehole failure modes and pore pressure effects, Computers and Geotechnics, Volume 37, Issues 1–2, January–March 2010, Pages 141-152.

[7] Gentzis T., N. Deisman, Richard J. Chalaturnyk, A method to predictgeomechanical properties and model well stability in horizontal boreholes, International Journal of Coal Geology, Volume 78, Issue 2, 1 April 2009, Pages 149-160.

[8] Lee H., S. Ong, M. Azeemuddin, H. Goodman. A wellbore stability model for formations with anisotropic rock strengths, Journal of Petroleum Science and Engineering, Volumes 96–97, October 2012, Pages 109-2109.

[9] Carvalho Coelho L., A. Claudio Soares, N. Francisco, F. Ebecken, J. Alves, L. Landau.The impact of constitutive modeling of porous rocks on 2-D wellbore stability analysis Original Research Article, Journal of Petroleum Science and Engineering, Volume 46, Issues 1–2, 15 February 2005, Pages 81-100.

[10] Zare-Reisabadi M.R., A. Kaffash, S.R. Shadizadeh (2012), Determination of optimal well trajectory during drilling and production based on borehole stability, International Journal of Rock Mechanics and Mining Sciences, Volume 56, December 2012, Pages 77-87.

[11] Gentzis T., (2009), Stability analysis of a horizontalcoalbed methane well in the Rocky Mountain Front Ranges of southeast British Columbia, Canada, International Journal of Coal Geology, Volume 77, Issues 3–4, 31 January 2009, Pages 328-337.

[12] TaoQingfeng, Ahmad Ghassemi, Poro-thermoelastic borehole stress analysis for determination of the in situ stress and rock strength, Geothermics, Volume 39, Issue 3, September 2010, Pages 250-259.

[13] Al-Ajmi Adel M., Robert W. Zimmerman, A new well path optimization model for increased mechanical borehole stability, Journal of Petroleum Science and Engineering, Volume 69, Issues 1–2, November 2009, Pages 53-62.

[14] Haimson B., Micromechanisms of borehole instability leading to breakouts in rocks, International Journal of Rock Mechanics and Mining Sciences, Volume 44, Issue 2, February 2007, Pages 157-173.

[15] HaoShu-qing, A study to optimize drilling fluids to improve borehole stability in natural gas hydrate frozen ground, Journal of Petroleum Science and Engineering, Volume 76, Issues 3–4, March 2011, Pages 109-115.

[16] Xu G., Q. Guo, Z. Zheng, J. McLennan, S. Green, A finite element poro-inelastic analysis of borehole problems, International Journal of Rock Mechanics and Mining Sciences, Volume 34, Issues 3–4, April–June 1997, Pages 342.e1-342.e10.

[17] Oliver G., Karpfinger F., Jocker J., Prioul R. Comparison between analytical and 3D finite element solutions for borehole stresses in anisotropic elastic rock, International Journal of Rock Mechanics and Mining Sciences, Volume 51, April 2012, Pages 53-63.

[18] Klee G., Rummel F., Williams A. Hydraulic fracturing stress measurements in Hong Kong. International Journal of Rock Mechanics and Mining Sciences, 1999, 36: 731-741.

[19] Jincai Zhang, Borehole stability analysis accounting for anisotropies in drilling to weak bedding planes, International Journal of Rock Mechanics and Mining Sciences, Volume 60, June 2013, Pages 160-170.

[20] JaroslavMackerle, Stability problems analysed by finite element and boundary element techniques — A bibliography (1994–1996), Finite Elements in Analysis and Design, Volume 26, Issue 4, 15 August 1997, Pages 337-353.

[21] J. Rutqvist, G.J. Moridis, T. Grover, S. Silpngarmlert, T.S. Collett, S.A. Holdich, Coupled multiphase fluid flow and wellbore stability analysis associated with gas production from oceanic hydrate-bearing sediments, Journal of Petroleum Science and Engineering, Volumes 92–93, August 2012, Pages 65-81.