International Journal of Civil Engineering and Environmental Science. Volume 3, Issue 1, (2015) 42-49
http://www.cayley-nielson.com/ijcees/

Fracturing Pressure in Oil/Gas Well Drilling

Bo Li
Key Laboratory of Data Storage Systems, Ministry of EducationHuazhong University of Science & Technology, 1037 Luoyu Road, Wuhan, China
E-mail: *ielibo@hust.edu.cn*

Abstract

During oil and gas well drilling, when the drilling fluid density is too high, not only tensile fracturing but also shear fracturing may occur on the wellbore. The possible fracturing modes and corresponding calculation formulas of fracturing pressure were present. Moreover, the influence of the magnitude and non-uniformity of in-situ stress, the pore pressure, and the formation strength on fracturing mode was quantitatively analyzed. The results showed that: the risk of shear fracturing was higher with small non-uniformity of in-situ stress; when the horizontal stress was small, shear fracturing and tensile fracturing both probably happened, and a higher in-situ stress leaded to less probability of tensile fracturing; the potential of tensile fracturing increased with the increasing of formation strength and pore pressure.

Keywords: drilling; wellbore stability; fracturing pressure; tensile failure; shear failure.

1. Introduction

Petroleum is one of the most important energy sources in the world [1-4]. Wellbore instability while drilling is a common but important problem that has puzzled the petroleum industry for long. The economic losses caused by wellbore instability reach more than one billion dollar every year [5]. The aim of wellbore stability research is to determine the range of drilling fluid density that can maintain the wellbore stable [6]. Proper mud density should satisfy following rules: the mud column pressure should be higher than the collapsing pressure and less than the fracturing pressure. Previous wellbore stability research mostly focused on collapsing pressure and revealed wellbore collapsing mechanism from different aspects such as mechanics and chemistry etc. [7-10]. Research on the fracturing pressure was comparably less, though some achievement was presented [9-15], the theoretical foundation was derived from the hydraulic fracturing theory [16], and only took the tensile fracturing into consideration with overlooking of the shear fracturing which may occur when tangential stress is the minimum principal stress. The experiment results revealed that shear failure may happen when wellbore pressure is high [17-18]. The aim of hydraulic fracturing is to establish a big and open tensile fracture to inject huge volume of the fracturing fluid and proppant. So shear fracturing has little effect on hydraulic fracturing [17-19], however, it is significantly important for wellbore stability because the wellbore will collapse when shear fracturing happens. In this paper, potential failure modes of the wellbore when the mud density is high were analyzed and presented the fracturing pressure calculation formula.

2. Stress distribution on the wellbore wall

When a borehole drilled, the drilling fluid replaces the rock, which definitely leads to stress concentration [20]. The maximum stress appears on the wellbore wall [21]. The effective stress on the wellbore wall of a vertical well is as following [21]:

$$\begin{cases} \sigma_r' = P_{wf} - \alpha P_p \\ \sigma_\theta' = -P_{wf} + (1 - 2\cos 2\theta)\sigma_H + (1 + 2\cos 2\theta)\sigma_h - \alpha P_p \\ \sigma_z' = \sigma_V - 2\mu(\sigma_H - \sigma_h)\cos 2\theta - \alpha P_p \end{cases} \tag{1}$$

Where σ_r', σ_θ', σ_z' are the radial, tangential and axial stress, P_{wf} is the wellbore pressure, P_p is the pore pressure, α is the Biot's coefficient, σ_V is the overburden pressure, σ_H and σ_h are the maximum and minimum horizontal in-situ stress, θ is the angle from the direction of the maximum horizontal stress to the radial line of the point on the wellbore.

3. Calculation model of fracturing pressure

In traditional wellbore stability analysis, fracturing pressure was determined by tensile failure [9-15]. What is ignored is that shear failure may also take place when the drilling fluid density is too high and the tangential stress is the minimum principal stress [17-19].

The minimum tangential stress appears at the direction of maximum horizontal stress ($\theta = 0^\circ$ or $\theta = 180^\circ$) [21-22]. At this direction the values of ($\sigma'_r - \sigma'_\theta$) and ($\sigma'_z - \sigma'_\theta$) all reach the maximum. Fig.1 shows the variation of effective stress with wellbore pressure when $\theta = 0^\circ$ or $\theta = 180^\circ$. The tangential stress decreases with the increasing of wellbore pressure. When the wellbore pressure is higher than 29MPa, the tangential stress becomes the minimum stress. The axial stress maintains constant. The radial stress increases with the increasing of wellbore pressure. If ($\sigma'_r - \sigma'_\theta$) or ($\sigma'_z - \sigma'_\theta$) exceeds the formation shear strength before tangential stress reaches the tensile strength, shear fracturing will occur.

We label the shear fracturing when σ'_r is the maximum stress as shear fracturing I and the shear fracturing when σ'_z is the maximum stress as shear fracturing II.

When the drilling fluid density is too high, the fracture is most likely to occur when $\theta = 0^\circ$ or $\theta = 180^\circ$, the effective stresses at the two points are as following:

$$\begin{cases} \sigma_r' = P_{wf} - \alpha P_p \\ \sigma_\theta' = -P_{wf} - \sigma_H + 3\sigma_h - \alpha P_p \\ \sigma_z' = \sigma_V - 2\mu(\sigma_H - \sigma_h) - \alpha P_p \end{cases} \tag{2}$$

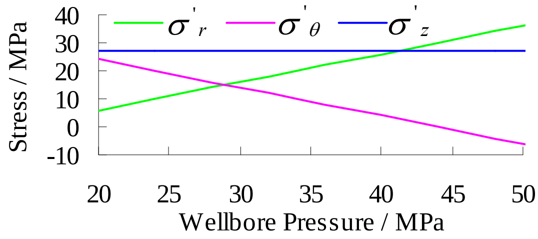

Fig. 1. Variation of principal stress with wellbore pressure at maximum horizontal stress direction.

It is assumed that the formation followed Mohr-Coulomb strength criterion [21]:

$$\sigma_1 = \sigma_3 \tan^2(\pi/4 + \varphi/2) + 2C\tan(\pi/4 + \varphi/2) \tag{3}$$

Where σ_1 and σ_3 is the maximum and minimum effective principal stress respectively; φ is the internal friction angle of the formation; C is the cohesion.

When radial stress is the maximum stress and the tangential stress is the minimum stress, Inserting Eqs.(2) into Eqs.(3), fracturing pressure of shear fracturing I can be got:

$$P_{\mathrm{I}} = \frac{K^2(3\sigma_h - \sigma_H) + (1-K^2)\alpha P_P + 2CK}{1+K^2} \tag{4}$$

Where $K = \tan(\pi/4 + \varphi/2)$.

When axial stress is the maximum stress and the tangential stress is the minimum stress, inserting Eqs.(2) into Eqs.(3), fracturing pressure of shear fracturing II can be got:

$$P_{\mathrm{II}} = \frac{K^2(3\sigma_h - \sigma_H) + (1-K^2)\alpha P_P - \sigma_V + 2\mu(\sigma_H - \sigma_h) + 2CK}{K^2} \tag{5}$$

Tensile fracturing takes place when the tangential stress reaches the tensile strength of the formation. fracturing pressure of tensile fracturing is as following [22]:

$$P_t = 3\sigma_h - \sigma_H - \alpha P_P + S_t \tag{6}$$

The fracturing pressure (P_f) in drilling process is the minimum value of P_{I}, P_{II} and P_t, to prevent any kind of failure taking place.

$$P_f = \min(P_{\mathrm{I}}, P_{\mathrm{II}}, P_t) \tag{7}$$

4. Influencing factors of fracturing modes

The calculation parameters are as follows: $\sigma_v = 46MPa$, $\sigma_H = 44MPa$, $\sigma_h = 34MPa$, $P_P = 20.6MPa$, $\alpha = 0.7$ $\mu = 0.25$ $C = 10MPa$ $\varphi = 30^\circ$, $S_t = 2.9MPa$.

4.1 The influence of in-situ stress magnitude

Fig.2 shows the variation of three kinds of fracturing pressure with the maximum horizontal stress when the in-situ stress non-uniform coefficient $M = 1.5$ ($M = \sigma_H / \sigma_h$) . With the increasing of σ_H, three kind of fracturing pressure increases approximately linearly, which means the greater the horizontal stress is, the wellbore is more difficult to fracture. he increasing rate of P_{II} is the fastest, and the increasing rate of P_{I} is the slowest. When σ_H is smaller than 52MPa, P_t is the minimum, tensile fracturing occurs first. When σ_H is higher than 52MPa, P_{I} is the minimum, shear fracturing Ⅰ occurs first. In this non-uniform stress coefficient, it is less likely to occur tensile fracturing when the in-situ stress is great, and the greater the in-situ stress is, the greater the possibility of shear fracturing Ⅰ is.

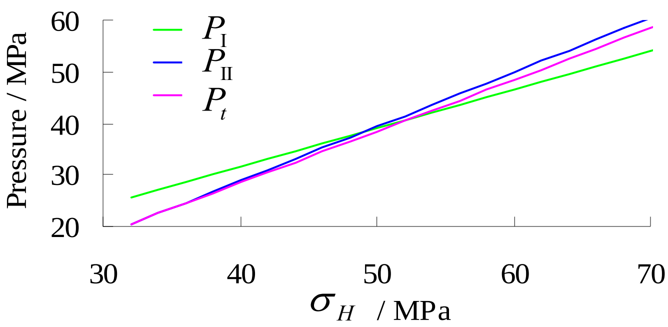

Fig. 2. The influence of in-situ stress magnitude on fracturing pressure.

4.2 The influence of non-uniformity of in-situ stress

Keep $\sigma_h = 34MPa$, only M changed, variation of the three kind of fracturing pressure is shown in Fig.3. As the value of M increases, three kind of fracturing pressure all reduced linearly, the possibility of wellbore fracturing increases with the increasing of in-situ stress non-uniformity. The decreasing rate of P_t is the fastest, and that of P_{I} is the slowest. Shear fracturing Ⅰ occurs first when M is smaller than 1.5. When M is bigger than 1.5, tensile fracturing occurs first. In some areas with little tectonic movement, the in-situ stress non-uniformity is small, the possibility of shear fracturing can not be ignored.

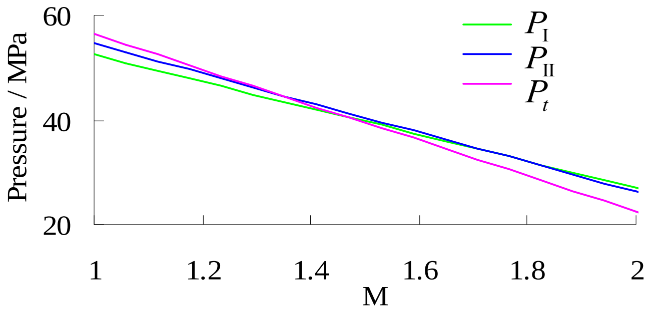

Fig. 3. The influence of in-situ stress non-uniformity on fracturing pressure.

4.3 The influence of pore pressure

Fig.4 shows the variation of fracturing pressure with pore pressure. When pore pressure increases from 10MPa to 40MPa, fracturing pressure increases linearly, but he growth rate of P_t is far less than P_{I} and P_{II}. When the pore pressure is less than 30MPa, shear fracturing I occurs first; when the pore pressure is higher than 30MPa, tensile fracturing occurs first. The greater the pore pressure is, tensile fracturing is more easily to occur.

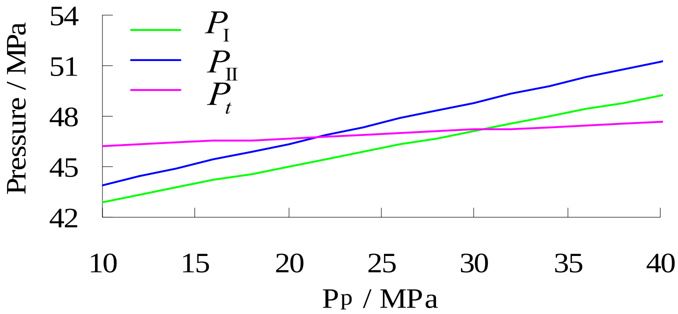

Fig. 4. The influence of pore pressure on fracturing pressure.

4.4 The influence of formation cohesion

Cohesion and internal friction angle are the parameters to reveal the formation strength characters in Mohr-Coulomb strength criterion. The relationship of tensile strength (S_t) and uniaxial compressive strength (UCS) is given by the Griffith criterion [22].

Fig.5 shows the variation of fracturing pressure with cohesion. The fracturing pressure increase linearly with the increasing of cohesion, which means the stability of the formation increases with higher cohesion. The increasing rate of P_{II} is the fastest and that of P_t is the slowest; when the cohesion is less than 5Mpa, shear fracturing II takes place first; when the cohesion is between 5Mpa and 12Mpa, shear fracturing I takes place first; when the cohesion is higher than 12Mpa, tensile fracturing takes place first. When the cohesion is small, the probability of shear fracturing can not be ignored.

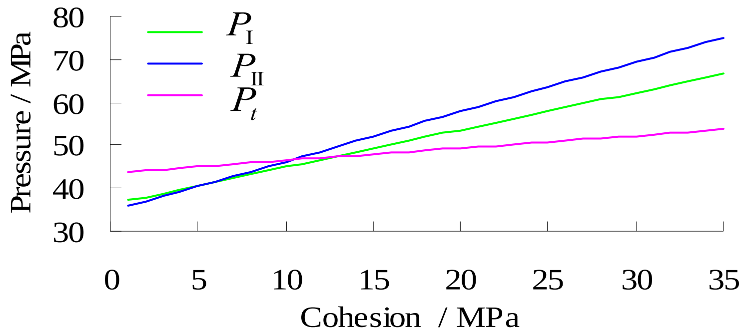

Fig. 5. The influence of cohesion on fracturing pressure.

4.5 The influence of internal friction angle

Fig.6 shows the variation of three kind of fracturing pressure with the internal friction angle. The pressure increases with the internal friction angle increasing. The increasing rate of the shear fracturing pressure decreases with the increasing of internal friction angle, but the increasing rate of the tensile fracturing pressure increases gradually. Shear fracturing Ⅰ always occur first with the parameters this paper selected.

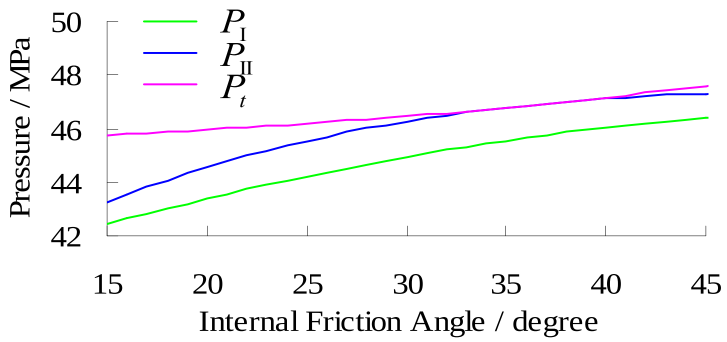

Fig. 6. The influence of internal friction angle on fracturing pressure.

5. Case study

Fracturing pressure of Well-A in Dongfang13-1 gas-filed in China were calculated using the above model. The results are shown in Fig.8. The calculation parameters such as strength parameters, in-situ stress, pore pressure, etc are obtained by logging data. [22].

It can be seen from Fig. 7 that P_{I} is the minimum above 1200m, shear fracturing Ⅰ happens first, thus the P_{I} can be regarded as the fracturing pressure of this interval. Shear fracturing still appears first from 1200m to 1500m, but these two shear fracturing modes exist alternatively; the difference of three kinds of fracturing pressure below 1500 m are small and also exist alternatively, while there are mainly tensile fracturing. The minimum of these three kinds of fracturing pressure should be regarded as the fracturing pressure and the upper limit of safe mud density window in wellbore stability analysis.

Shear fracturing won’t lead to fracturing fluid leakage in hydraulic fracturing, the leakage of fracturing fluid only happens after the fracturing opened, and thus the initial opening and re-opening of shear fracturing are both on the same shear fracturing plane, so the initial opening fracturing pressure is equal to the re-opening pressure [18]. There was a leak off test at 660m depth in Well-A, the result showed the initial opening fracturing pressure is equal to re-opening fracturing pressure, it indicated that the first fracturing was shear fracturing.

According to the statistics by Liu JZ etc.[18], approximately 50% of the fracturing curves showed that the initial opening fracturing pressure was equal to the re-opening fracturing pressure in Dagang oil-field of China. The hydraulic fracturing tests in San Andreas Fault showed that the formation initial fracturing pressure above 500m was bigger than the re-opening fracturing pressure; but below 500m they were equal. The results implied that the formation above and below 500m belonged to different fracturing modes.

The fracturing mode is affected by in-situ stress and formation strength together. Overburden pressure in San Andreas Fault is the minimum stress [23], while overburden pressure in Dongfang13-1 gas-filed is the maximum stress. In addition, the formation of San Andreas Fault is older, so the variations of fracturing modes in these two areas are different, but they both show shear fracturing is very common. Although the shear fracturing pressure cannot be applied in hydraulic fracturing, it is very important in wellbore stability analysis.

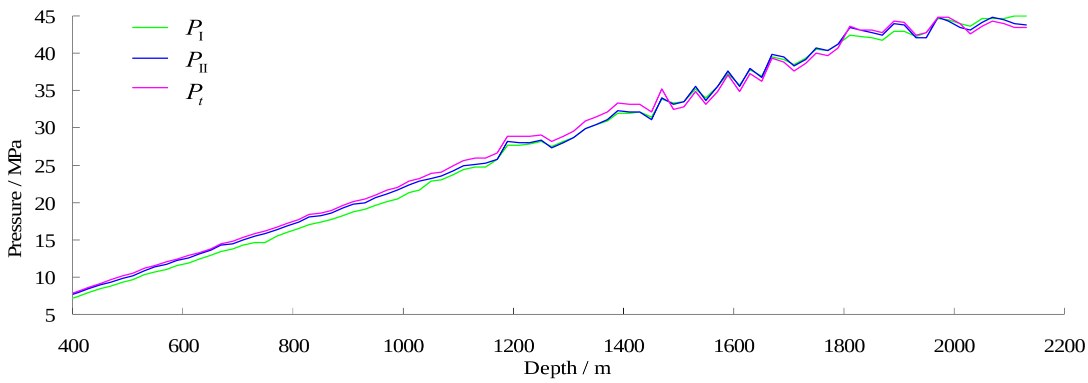

Fig. 7. Fracturing pressure of Well-A.

6. Conclusions

When the mud density is too high, no only tensile fracturing but also shear fracturing may occur on the wellbore wall. There are two types of combining forms of the stress that can cause shear fracturing, shear fracturing pressure calculation formula is deduced.

When the non-uniformity of in-situ stress is constant, the possibility of shear fracturing Ⅰ increases with the in-situ stress increasing; when the non-uniformity of in-situ stress is weak, shear fracturing easily appears on the wellbore wall, in addition, the potential of tensile fracturing increases with the non-uniformity of in-situ stress increasing; the higher the formation strength and pore pressure are, the shear fracturing is easier to occur.

Shear fracturing must be considered in wellbore stability analysis, take the minimum of shear fracturing pressure and tensile fracturing pressure as the upper limit of mud density.

References

[1] Demirbas A. Fuels for petroleum, coal and biomass. Energy Educ Sci Technol Part A 2012; 29:701-705.

[2] Cheng LH, Bi XJ, Ni YT. Oilfield produced water treatment by ozone-enhanced flocculation. Energy Educ Sci Technol Part A 2012; 29:91-98.

[3] Zhang J, Li W, Li CY, Wang BS. Real-time PCR-based, quantitative detection of sulfate-reducing bacteria in oilfield sewage using a TagMan-LNA probe. Energy Educ Sci Technol Part A 2012; 30:281-286.

[4] Xue BX, Li W, Li TY, Li CY, Hao JM. Study of the environmental management schema for mixedresidential areas near extra-low-permeability oilfield based on PVC-blend hollow-fiber membrane wastewater. Energy Educ Sci Technol Part A 2012; 30:293-302.

[5] Mohammad E Z. Mechanical and physical-chemical aspects of wellbore stability during drilling operations. Journal of Petroleum Science and Engineering 2012; 82-83:120-124,.

[6] McLean MR, Addis MA. Wellbore Stability Analysis: A Review of Current Methods of Analysis and Their Field Application. SPE/IADC Drilling Conference1990. SPE. 19941-MS.

[7] Bradley WB. Mathematical concept-stress cloud can predict borehole failure. Oil&Gas J 1979; 77: 92–102.

[8] Aadnoy BS, Rogaland U, Chenevert ME. Stability of highly inclined boreholes. SPE Drilling Engineering 1987. 2: 364-374. SPE. 16052.

[9] Qiu ZS, Xu JF, Lü KH, Yu LX, Huang WA, Wang ZM. A multivariate cooperation principle for well-bore stabilization. Acta Petrolei Sinica 2007;28: 117-119 [in Chinese].

[10] Roshan H, Fahad M. Chemo-poroplastic analysis of a borehole drilled in a naturally fractured chemically active formation. Int J of Rock Mechanics and Mining Science 2012; 52: 82–91.

[11] Eaton B A. Fracture Gradient Prediction and Its Application in Oilfield Operations. JPT 1969; 21:1353-1360,.

[12] Huang RZ. A model for predicting formation fracturing pressure. Journal of East China Petroleum Institute1984; 4:335-347.

[13] Wang GH, Xu TT. Reo-mechanics analysis for borehole stability. Drilling & Production Technology 2005;28: 7-11.

[14] Guo KJ,Chang PF. Study on prediction of fracturing pressure of shallow layer. Chinese Journal of Rock Mechanics and Engineering 2004; 23: 2484-2487.

[15] Zhang H, Li JF, Yuan SJ. Probe into well logging evaluation of borehole wall stability in tarim basin. Journal of Southwest Petroleum University 2008; 30: 33-36.

[16] Hubbert MK, Willis DG. Mechanics of hydraulic fracturing. Mem. - Am. Assoc. Pet. Geol, 1972; 28: 239-257.

[17] Liu JZ, Chao XL, Lin ZQ. Shear fracturing during the proess of hydrofractures. Journal of Seismological Research 1984; 7: 253-262.

[18] Liu JZ, Li ZQ. Experiment on and Analysis of the theory of Hydraulic Fracturing stress Measurements. Chinese J of Rock Mechanics and Engineering 1986; 5: 267-276 [in Chinese].

[19] Liu JJ, Feng XT, Pei GH. Study on mathematical model of three dimensional hydraulic fracturing. Chinese J of Rock Mechanics and Engineering 2003, 22: 2042-2046 [in Chinese].

[20] Geertsma J. Some rock-mechanical aspects of oil and gas well completion. In: Proc. of European Off-Shore Petroleum Conference and Exhibition 1978. London: 24-27.

[21] Fjær E, Holt RM, Horsrud P. Petroleum Related Rock Mechanics. Elsevier, 2008.

[22] Chen M, Jin Y, Zhang GQ. 2008. Petroleum related rock mechanics. Science Press 2008. Beijing.

[23] Keys WS, Wolff RG, Bredehoeft JD, Shuter E, Healy JH. In-situ stress measurements near the San Andreas Fault in central California. Journal of geophysical research 1979; 84:1583-1591.