Science Arena Publications
Specialty Journal of Engineering and Applied Science
ISSN: 2520-5943
Available online at www.sciarena.com
2020, Vol, 5 (2): 35-48

The Impact of Well Specifications and Well Inclination on Fracture Pressure

Hossein Mohammadi[1]*, Friborz Rashidi[2], Mohammad Tabaeh Hayavi[3]

[1]Department of Petroleum Engineering, University of Amirkabir, Tehran, Iran.
[2]Professor, Department of Chemical Engineering, Amirkabir University of Technology, Tehran, Iran.
[3]Department of Petroleum Engineering, Omidiyeh Branch, Islamic Azad University, Omidiyeh, Iran.

***Corresponding Author**

Abstract: *Hydraulic fission has been successfully performed in the world for more than several decades and its application is increasing. However, in our country, due to the high pressure of reservoirs, there is not much interest in this work and few cases that have been performed, have not been successful due to inadequate geomechanical studies. The aim of this study is to investigate the effect of well characteristics and well inclination on fracture pressure. One of the most important issues in hydraulic fission is the right location for hydraulic fission. In other words, in which layer or depth, this operation should be performed. The effective parameters in selecting the appropriate depth for hydraulic fission include the degree of water saturation, that porosity, and geomechanical properties of the reservoir in order of their priority. Porosity affects on well yield and geomechanical properties affect on fracture pressure. There are two views to study and analyze the hydraulic fracture process. One is the mechanical fracture method and the other is the classical method, based on the theory of elasticity. The geomechanical parameters affecting the fracture pressure include Young's modulus, Poisson's coefficient and Biot coefficient. Poisson's coefficient was determined to be the most effective parameter on hydraulic fracture pressure and fission. In this study, the parameters affecting the fracture pressure were investigated.*

Keywords: *Fracture pressure, well specifications, hydraulic fracturing.*

INTRODUCTION

In the oil industry, detecting the best candidate wells for various operations is a common process. In the process of choosing a candidate well for hydraulic drilling, the goal is to select one or a group of wells or zones for the operation that are most likely to succeed. Studies have revealed that if wells and candidate layers are chosen well, it can considerably increase production, especially in wells with high crust and low permeability. Most carbonate reservoirs have low permeability and they can be produced economically if they are hydraulically fractured.

Fluid injection in the slit layer process increases the fluid pressure inside the well. This increase in pressure can exceed the tensile strength of the rock and cause tensile fracture in the well. Tensile fractures are of two general types, vertical tensile fractures, which occur when the tangential tension on the well wall exceeds the smallest horizontal tension plus the tensile strength of the rock around the well. This type of fracture occurs in the hydraulic fracturing. Horizontal tensile fractures are rarely seen in wells and often occur in shallow wells and cylindrical tensile fractures, which occur when the radial tension on the well wall exceeds the tensile strength of the rock around the well (Habibnia, 2016).

Hydraulic fracture can be defined as the process by which a fracture in a reservoir rock begins and spreads by hydraulic loading created by the fluid injection into a part of a well. Factors that can affect the fracture start pressure include well conditions, fluid properties used in hydraulic fission, reservoir rock properties, and the way of well completion operations. For a successful hydraulic fracture operation, the relationship between these parameters and the fracture pressure must be specified. In this research, using MATLAB software, the effect of geomechanical parameters such as Young's modulus, Poisson's ratio and biot coefficient, as well as well characteristics such as well inclination from vertical position, well azimuth and completion operations such as lattice on fracture start pressure are analytically and numerically addressed. The information obtained in this research can be used in predicting fracture start pressure and selecting candidate layers that have the lowest fracture pressure, as well as in inclination wells by choosing the right inclination and azimuth of the well, as well as completing operations (lattice), it can have a lot of effects on reducing costs.

Theoretical Bases of the Research

Properties of rock

1. Young's Mudulus

The Young's modulus, or modulus of elasticity, is the ratio of tension to strain of linear solids below the yield strength, that in this case, Hooke's law is applicable and the modulus of elasticity is constant. The Young's modulus for the rock can be static or dynamic depending on the load rate. The modulus of dynamic elasticity is higher than static, but the higher the strength of the rock, the closer these two values are. The modulus of dynamic elasticity depends on the speed of propagation of the waves and therefore on the type of rock, texture, density, foraminiferation, the amount of tension applied and the amount of water and so on. Young's modulus depends on factors such as temperature, frequency loading speed, test type, etc. (Masihi, 2006).

2. Poisson ratio

Compressive tension applied to a block of material along a particular axis leads to a shortening of the length along that axis and also leads to expansion in all directions perpendicular to that axis. The ratio of the strain perpendicular to the applied tension (expansion) to the strain along the applied tension (shortening) is called the Poisson's ratio. In other words, it is the ratio of lateral (transverse) to axial (longitudinal) strain.

Using the Poisson's ratio value in adjacent locations, it should be possible to predict the precedence of corrosion gap in areas. In the lower sections, we will show the priority of the precedence of corrosion gap of the layer over the Poisson. Acoustic diagram measurements make it possible to determine the Poisson ratio in the formation.

3. Biot coefficient (α)

For the first time in 1923, the effect of porosity pressure on vertical tension called effective tension (〖σ ^ '〗 _ v) was presented by Terzagi using a one-dimensional equation (Anderson, 1951):

$$\sigma'_v=\sigma_v-P_p \tag{1}$$

A theory was then proposed in which it included both diffusion and deformation processes observed in elastic materials (Ghorbani, 2016). Based on this theory, the effective vertical tension (σ'_v) in the rock matrix is calculated according to the following equation:

$$\sigma'_v=\sigma_v-\alpha P_p \tag{2}$$

Here $\sigma'_v$is equal to the effective vertical tension in terms of Psi, α is equal to the prolastic bio constant, and $P_p$is equal to the fluid pressure inside the rock pores, or in other words the pore fluid pressure in terms of (Psi). For obtaining Bio coefficient, the following equation can be used:

$$\alpha=\frac{\Delta V_p}{\Delta V_g}=1-\frac{k_b}{K_g} \tag{3}$$

Here K_b is the bulk modulus of the drained porous rock and $k_g$is the bulk modulus of the solid particles making up the rock, ،ΔV equals the total volume change of the rock and ΔV_p is equal to the change in pore volume. The values of the main tensiones at different depths are affected by the fluids that are present in the pores and cracks of the rock. To describe the small deformations of saturated porous materials, it is necessary to use the theory of proxies. If α is zero, this means that the rock is almost non-porous. In completely porous rocks such as sandstone, it is close to one (Habibnia, 2016).

Fracture pressure

There are two perspectives for studying and analyzing the hydraulic fracture process. One is the mechanical fracture method and the other is the classical method, which is the theory of elasticity. Most research conducted on the design and analysis of a hydraulic rupture process based on the classical method that is the theory of elasticity.

1. Theory of fracture mechanics

The well wall has cracks, fissures and joints that due to the application of fluid pressure, hydraulic fracture starts and spreads from the site of these discontinuities. So, from the point of view of fracture mechanics, hydraulic rupture is a process of occurrence and growth of cracks in well wall discontinuities. From this perspective, due to the infiltration of the injection fluid into the cracks in the well wall, the intensity of tension at the tip of the well wall cracks increases with increasing fluid pressure and in critical conditions, it leads to crack growth and expansion, and it is a general criterion for crack growth in the process of hydraulic rupture based on the mechanical fracture method as follows (Ayatollahi, 2008):

$$k_I=k_{IC} \tag{4}$$

Where $k_I$is the tension intensity coefficient at the crack tip, $k_{IC}$is the critical tension intensity factor (toughness instead of rock).

2. Theory of elasticity

In the theory of elasticity, rupture starts when the tangential tension around the well has reached the tensile strength of the rock mass around the well, and as the injection pressure continues, the resulting fracture and rupture grow and expand. At each point of the wall, three main tensiones, maximum main tension ($\sigma_{\text{۱}}$), intermediate main tension ($\sigma_{\text{۲}}$) and minimum main tension ($\sigma_{\text{۳}}$) are applied to the well, which have been indicated in the following figure (Erdogan and Sih, 1963):

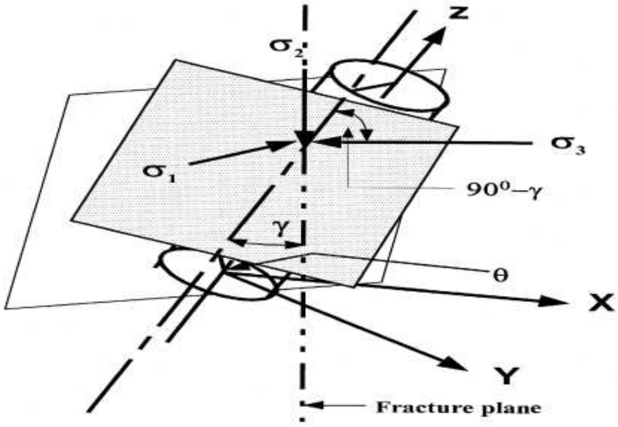

Figure 1: The main tensiones on the well wall (Hossain et al., 2000).

If we consider the well pressure as the main maximum tension, the main tensiones entering the well wall will be in the form of Equations (5) to (7) (Hayavi and Abdideh, 2016):

$$\sigma_{۱}=\sigma_r \tag{5}$$

$$\sigma_{۲} =\frac{۱}{۲} [(\sigma_\theta + \sigma_{z\theta}) + \sqrt{(\sigma_\theta - \sigma_{\theta z})^{۲} + ۴\tau_{\theta z}{}^2}] \tag{6}$$

$$\sigma_{۳} =\frac{۱}{۲} [(\sigma_\theta + \sigma_{z\theta}) - \sqrt{(\sigma_\theta - \sigma_{\theta z})^{۲} + ۴\tau_{\theta z}{}^2}] \tag{7}$$

According to the theory of elasticity, a crack is created when the intra-well pressure (P_w) increases as much that the most negative principal effective tension equals to the tensile strength (T_0).

$$\sigma_{۳} - P_p = -T_0 \tag{8}$$

Among the three main tensiones above, well pressure never becomes negative. Between $\sigma_{۳}$and$\sigma_{۲}$, with increasing well pressure, $\sigma_{۳}$is more negative than$\sigma_{۲}$. Therefore, combining equations (7) and (8), the fracture equation is as follows:

$$\sigma_{۳} - P_p= \frac{۱}{۲} [(\sigma_\theta + \sigma_{z\theta}) - \sqrt{(\sigma_\theta - \sigma_{\theta z})^{۲} + ۴\tau_{\theta z}{}^2}]- P_p=-T_0 \tag{9}$$

Equation (9) is the equation of fracture pressure in general, using this equation, the fracture pressure at any point of the well with any inclination (i) and azimuth (α) is obtained numerically.

Parameters affecting fracture pressure

1. Rservoir Geomecanics propeties

Fracture pressure is affected by each of the geomechanical properties of the reservoir as the considered properties have two direct and indirect effects on the fracture pressure. Considering their direct effect, due to their properties, they affect on the fracture pressure. Consiidering their indirect effect, they affect on the tensiones. For example, the higher the Poisson's coefficient, the less resistance it will have in loading, and it will break with the less tension, but on the other hand, the horizontal tensiones which are resulted from overburden tension, depend on the Poisson's coefficient. As the higher the Poisson's ratio, the greater the horizontal tensiones, thus the fracture pressure increases. The reservoir and geomechanical parameters used for numerical analysis have been shown in Table (1).

Table 1: Geomechanical and reservoir parameters

Overburden tension	15000Psi
Poisson's ratio	0.3
Tectonic strain in the direction of minimum horizontal tension (ε_h)	0.14
Tectonic strain in the direction of maximum horizontal tension (ε_H)	0.5
Initial reservoir pressure	5000Psi
Young's module	$10*10^6$ Psi
Biot coefficient	0.68
Thermal expansion coefficient	$4.34*10^{-6}$(1/F)

2. Tension

For this fracture in the rock to happen in the depths of the earth, the well pressure overcomes the tensions around the well that these tensions, the overburden tension,the minimum and maximum horizontal tensions that are caused by overburden and tectonic tension, which will change with the change of overburden tension and horizontal tensiones. If the overburden tension applied to a reservoir changes, the horizontal tensions and fracture pressures will change as follows.

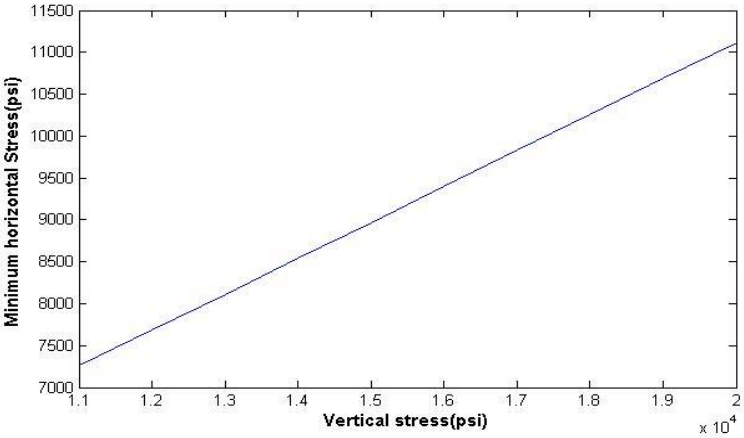

Figure 2: Changes of minimum horizontal tension in terms of overburden tension.

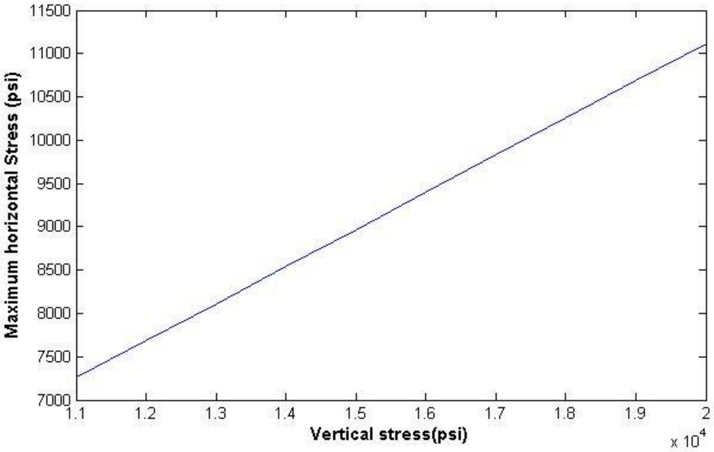

Figure 3: Changes of maximum horizontal tension in terms of overburden tension.

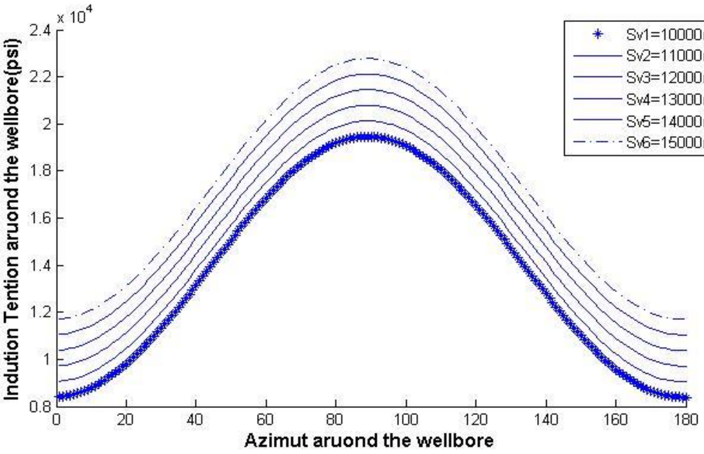

Figure 4: Changes in tangential tension around the well based on azimuth ratio of maximum horizontal tension at different overburden tensions.

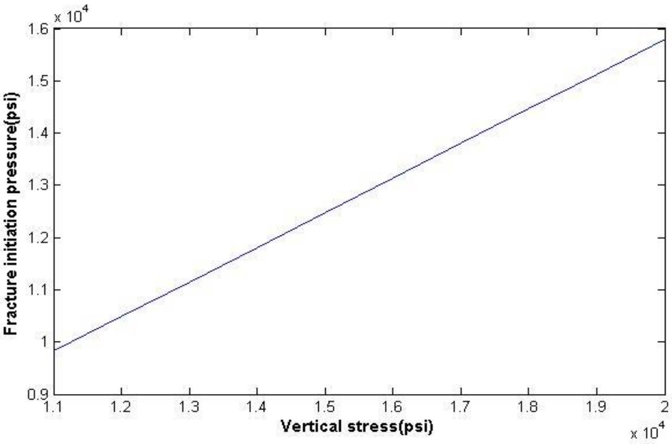

Figure 5: Changes in fracture pressure in overburden tension.

As the overburden tension increases, all tensions affected by the overburden tension, including the minimum horizontal tension, the maximum tension, and the tangential tensions and fracture tensions increase. As the overburden tension increases by 1000 psi, the minimum and maximum horizontal tensiones increase by 275 psi and 360 psi, respectively, and the fracture pressure increases by 600 psi.

3. The fluid effect of hydraulic gap

Viscosity and temperature are among the fluid properties of hydraulic fracture that affect on the fracture pressure, that we will discuss about the effect of temperature here. Decreasing the fluid temperature of the gap causes tension changes. Gaps resulted from heat is typically observed during the water injection process. Especially when there is a big difference between the temperature of the injected water (cold) and the reservoir (hot water). The typical response is a sudden increase in injectability after a significant period of constant injection. This indicates that the reservoir rock has gradually cooled during the cold water injection process. The reservoir rock shrinks due to cooling, and eventually the slightest in situ tension decreases to a level below the well injection pressure. This process creates a gap that provides a larger contact surface with the formation. As a result, there is a significant increase in injectability. The length of the gap is limited to the size of the cooled area. This process is usually called a heat gap.

4. Effect of well specifications

The parameters of the well that affect on the fracture pressure are:

4-1-Effect of well radius

Based on the following equation, changes in the well radius cause a change in the induced tensions and this also causes a change in the fracture start pressure. Increasing the well radius reduces the starting pressure.

$$\sigma_{\theta\theta}=\frac{1}{2}(\sigma_x+\sigma_y)\{1+\frac{r_w{}^2}{r^2}\}-\frac{1}{2}(\sigma_x+\sigma_y)\{1+\frac{3r_w{}^4}{r^4}\}\cos 2\theta-P_w\frac{r_w{}^2}{r^2} \tag{10}$$

$$\sigma_{rr}=\frac{۱}{۲}(\sigma_h+\sigma_H)\times(1-\frac{R^{۲}}{r^{۲}})+\frac{۱}{۲}(\sigma_h-\sigma_H)(۱-\frac{۴R^{۲}}{r^{۲}}+\frac{۳r_w{}^{۴}}{r^{۴}})\cos ۲\theta+P_w\frac{r_w{}^{۲}}{r^{۲}} \tag{11}$$

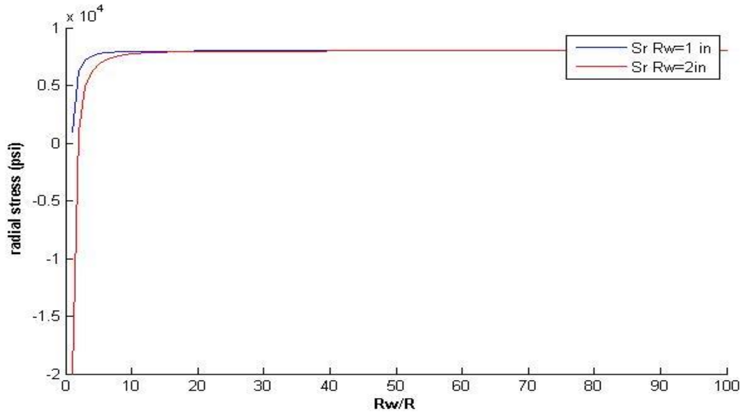

Figure 6: Graph of changes in radial tension in terms of (r / Rw) in different radii

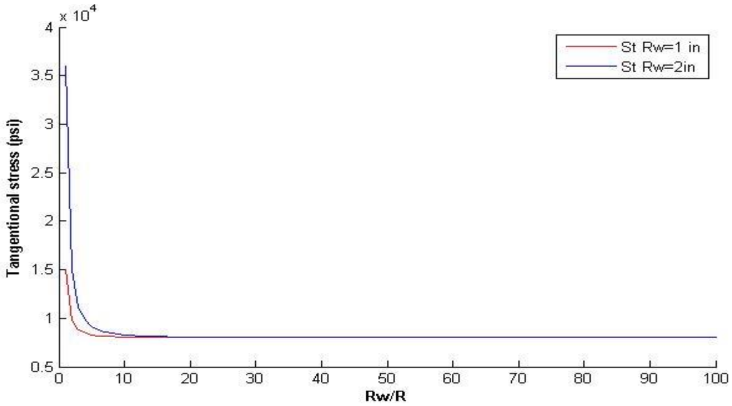

Figure 7: Graph of changes in tangential tension in terms of (r / Rw) in different radii.

Considering Figure (7), with increasing the radius of the well, the tangential tension around the well decreases and the lower the tangential tension, the pressure required for failure decreases. Therefore, with increasing the radius of the well, the fracture pressure decreases and also according to Figure (6), by increasing the radius of the well, the radial tension increases.

4-2. Azimuth and well inclination

The tensions around the well will change with the change of inclination and azimuth of the well, and consequently, the fracture pressure will change. Using the numerical method, the inclination and azimuth with the lowest fracture pressure can be obtained and the points of the well environment where the fracture occurs cane be found. According to the definition of fracture:

If $\sigma_{۲} - P_p = -T_0$ → break

If we exclude the sum of tensile tension and pore pressure, the equation is as follows:

$$\sigma_{۳} = \frac{۱}{۲}\left[(\sigma_{\theta} + \sigma_{z\theta}) - \sqrt{(\sigma_{\theta} - \sigma_{\theta z})^{۲} + {}^{۴}\tau_{\theta z}{}^{2}} \right] = 0 \tag{12}$$

From solving the equation above, the following equation is obtained:

$$\sigma_{\theta} = \frac{\tau_{\theta z}{}^{2}}{\sigma_{z\theta}} \tag{13}$$

$$\sigma_x{}^0 + \sigma_y{}^0 - 2*(\sigma_x{}^0 - \sigma_y{}^0)\cos 2\theta - 4\tau^0{}_{xy}\sin 2\,\theta - P_w - 2\,\eta\,(P_w - P_{f0}) = \frac{\tau_{\theta z}{}^{2}}{\sigma_{z\theta}} \tag{14}$$

$$P_w = \frac{\sigma_x{}^0 + \sigma_y{}^0 - 2*(\sigma_x{}^0 - \sigma_y{}^0)\cos 2\theta - 4\tau^0{}_{xy}\sin 2\,\theta + 2\eta P_{f0}}{1+2\eta} \tag{15}$$

In the normal and usual condition, in which $\sigma_h > \sigma_H \quad \sigma_v >$, the fracture pressure is numerically in each inclination and the azimuth is as follows.

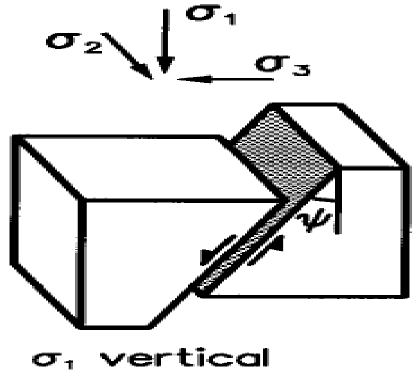

Figure 8: Normal tension regime

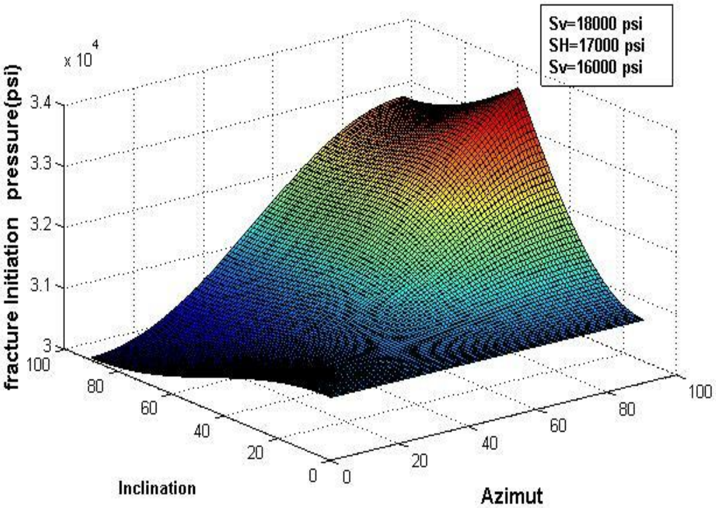

Figure 9: Changes in fracture pressure in inclination and different azimuths in normal regime

Regarding the figure above, the lowest fracture pressure occurs at a inclination of 90 degrees and the azimuth of zero degree. In other words, if we dig a horizontal well along the maximum horizontal tension, we will have the lowest failure pressure.

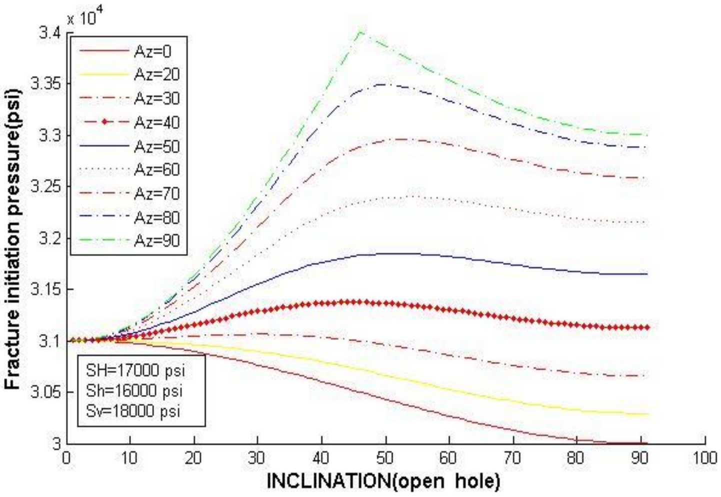

Figure 10: Changes in fracture pressure by changing the inclination in each fixed azimuth in the normal fault regime

If we observe the fracture pressure changes in different inclinations, we observe that by keeping the well azimuth (lines) constant, the lowest fracture pressure occurs in the 90 degree inclination and zero degree azimuth. In other conditions, the fracture pressure decreases up to 30 ° azimuth with increasing well inclination, but after 30 azimuth, the failure pressure increases with increasing well inclination. So that in 90 degree azimuth, we will have the highest increase in fracture pressure for 90 degree inclination change. The higher the well azimuth, the greater the failure pressure change relative to the well inclination.

In the reverse fault regime $if\ \sigma_H > \sigma_h > \sigma_v$, the reverse fault regime that can be caused by tectonics in the area and the distribution of tensions around the well will be different from the normal state of change. Therefore, the pressure of fractures will also change compared to normal condition.

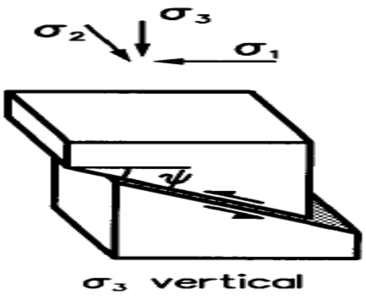

Figure 11: Inverse fault regime

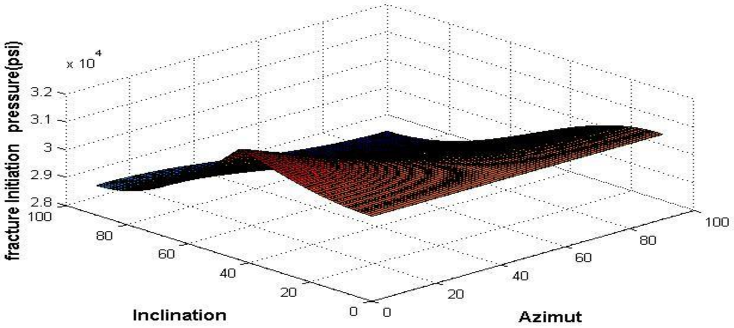

Figure 12: Fracture pressure changes in azimuth and various inclinations in the reverse tension regime.

According to Figure (12), the lowest fracture pressure is related to the inclination of 90 and azimuth 90, ie in the case of reverse fault regime along the minimum horizontal tension, the lowest fracture pressure is created and the fracture pressure in this case will be less than normal, so that the minimum failure in normal mode is 13,000 psi, and in reverse mode, it is 12,000 psi. Therefore, the presence of tectonics in the region is considered a point for fracture pressure.

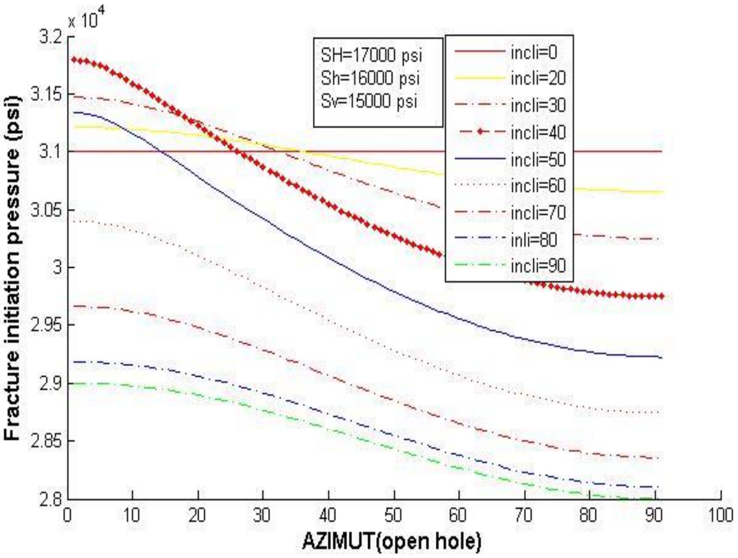

Figure 13: Changes in fracture pressure based on inclination changes in constant azimuth in reverse tension regime

Fracture pressure changes relative to azimuth in the reverse regime, in contrast to the normal state, occur at all inclinations in azimuth 90 at the lowest fracture pressure and also, the fracture pressure changes relative to azimuth are greater in the 50-degree inclinations than in the other inclinations. In the reverse tension regime, wells drilled on a plate containing the minimum horizontal tension have a lower fracture pressure than other plates.

5. Effect of completion operations

Most dug wells are cemented, and wall piped that for production, lattice operations must be performed. Cement work, wall pipes each affect on the distribution of tensions around the well, but lattice work causes the distribution of new induced tensions around the well and the lattice. Here we do lattice work on a well before we do the cement work and the wall pipe to check how the fracture pressure in an open well will change after lattice work. When a well is drilled, new inductive tensions are created around the well and these induced tensions continue up to a certain radius, then their effect disappears. It is the same for the lattice work. By creating a lattice around the well, new main tensions are created around the lattice that are affected by the induced tensions around the well and the main tensions. And like wells, tangential, shear and radial tensions and the three main tensiones around the lattice are created.

In the new model, we consider the lattice as a well. As we mentioned before, the main tensions around the well are the main ones. In lattice work, we assume that the length of the lattice is in the range of inductive tensions around the well, and we assume that the gap has started from the wellhead.

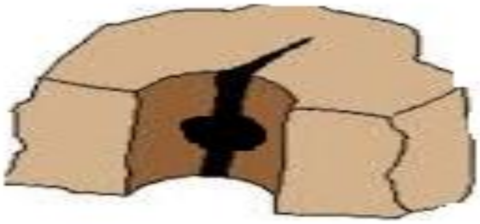

Figure 14: Lattice and gap created from the wellhead

Therefore, at the wellhead, the tensions around the lattice are 100% of the induced tensions around the well, and the main tensions that affect on the lattice are the main tensions around the well that we show these main tensions around the well around the lattice and obtain the main and inductive tensions around the lattice based on the main tensions around the well.

The main tensions around the lattice can be calculated as follows:

$$\sigma_{۱}=\sigma_r \qquad (16)$$

$$\sigma_{۲\mathrm{p}} =\frac{۱}{۲} \left[(\sigma'_{\theta p} + \sigma'_{z\theta p}) + \sqrt{(\sigma'_{\theta p} - \sigma'_{z\theta p})^{۲} + ۴{\tau'_{\theta zp}}^2} \right] \qquad (17)$$

$$\sigma_{۳\mathrm{p}} =\frac{۱}{۲} \left[(\sigma'_{\theta p} + \sigma'_{z\theta p}) - \sqrt{(\sigma'_{\theta p} - \sigma'_{z\theta p})^{۲} + ۴{\tau'_{\theta zp}}^2} \right] \qquad (18)$$

Lattice wall fracture occurs when the minimum effective principal tension equals the tensile tension:

$$\sigma_{۳}-\alpha P_p=-T \qquad (19)$$

By solving the above equation, the fracture pressure is numerically obtained. If we ignore the tensile tension and the pore pressure, the fracture pressure equation is as follows:

$$\sigma'_{\theta p}=\frac{{\tau'_{\theta zp}}^2}{\sigma'_{z\theta p}} \qquad (20)$$

$$P_{wbp}=\frac{\sigma_{xp}'+\sigma_{yp}'-2*(\sigma_{xp}'-\sigma_{yp}')\cos 2\theta_p-4\tau'_{xyp}\sin 2\,\theta_p+2\eta P_{f0}}{1+2\eta} \qquad (21)$$

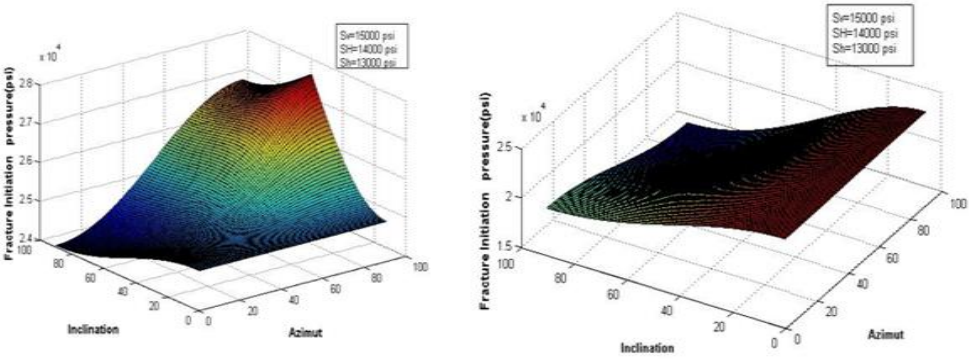

Figure 15: Picture on the left: Fracture pressure in each azimuth and inclination without lattice work. Picture on the right: Fracture pressure in each azimuth and inclination with lattice work (normal tension regime)

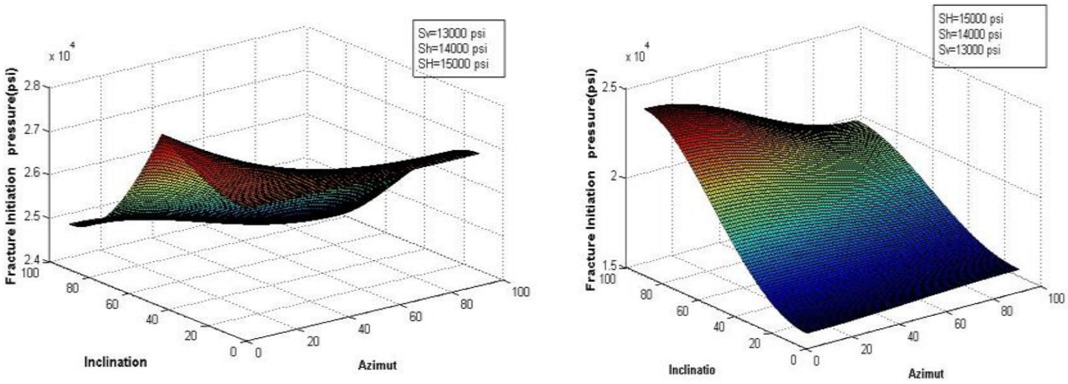

Figure 16: Picture on the left: Fracture pressure in each azimuth and inclination without lattice. Picture on the right: Fracture pressure in each azimuth and inclination in lattice mode (strike-slip tension regime).

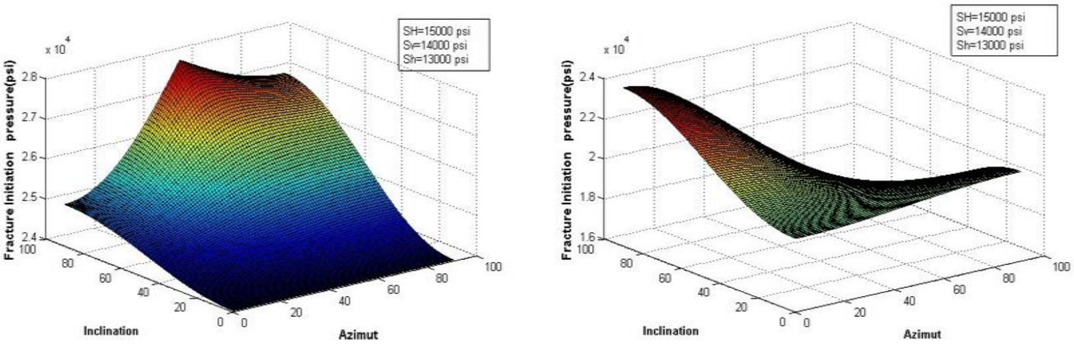

Figure 17: Picture on the left: fracture pressure in each azimuth and inclination without lattice. Picture on the right: fracture pressure in each azimuth and inclination in lattice mode (reverse tension regime).

Based on Figure (15), in normal condition, the minimum fracture pressure in the 90 and zero degree inclination equals to 24,000 psi, which is reduced to 19,600 psi in the case of lattice work. Based on Figure (16) in the reverse case, the minimum fracture pressure in the inclination and azimuth 90 and 90, which equals to 24,000 psi, the fracture pressure is reduced to 20,400 psi with lattice work. According to Figure (17) in the condition of slip stretch, the minimum failure pressure in inclination and azimuth of zero and zero, which equals to 24,000 psi, is reduced to 200,000 psi in the case of lattice work. Therefore, by creating a lattice, the failure pressure can be significantly decreased. It is also noteworthy that in locations that normally (without lattice) had the highest fracture pressure, when we do lattice work, the fracture pressure further decreases.

6. Excavating operation

Rocks in the depths of the earth due to overburden tensions or during drilling, mud pressure that is applied to them from a certain radius of the well, get out of elastic state and show plastic behavior. When the stone enters from the elastic to the plastic stage, it will not have the initial resistance, so its resistance to fracture reduces. Considering the fact that with increasing the radius of the well, the effect of induced tension decreases, therefore, the higher the plastic radius, the lower the effect of induced tensions. Below, we examine under tangential tensions in the elastic and elastoplastic states.

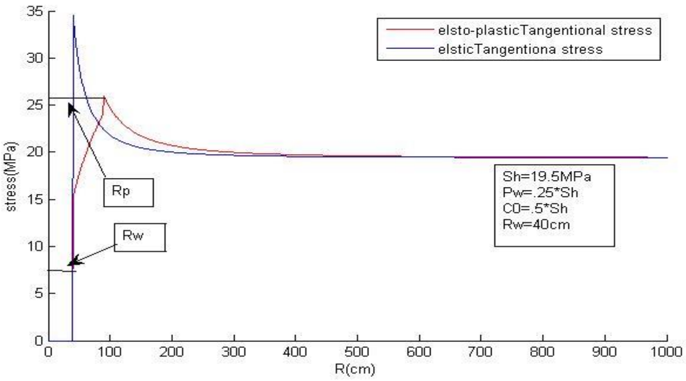

Figure 18: Tangential tension around the well in elastic and elastoplastic mode according to Terska criteria.

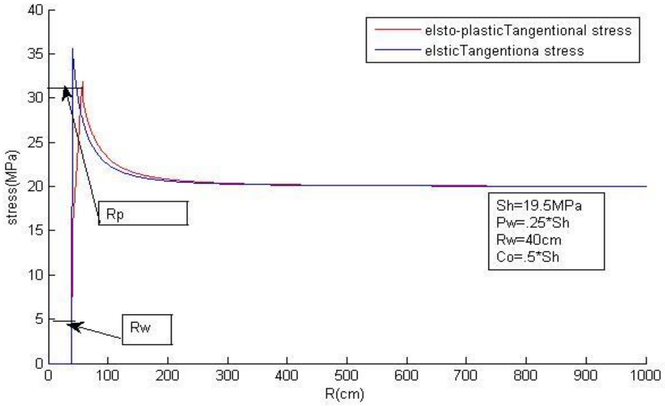

Figure 19: Tangential tension around the well in elastic and elastoplastic mode using Moore-Columb criterion

Both of the above figures display tangential tension in the elastic and elastoplastic (real) states. In Triska criterion, the tangential tension has decreased from 34 MPa to 25 MPa. And in the Moore-Columbus criterion, because the plastic radius (R_p) is less than that of the Triska, the tangential tension is reduced from 34 MPa in the elastic state to 30 MPa. Therefore, in reality, the fracture pressure will be less in the real state than in the hypothesis that we considered elastic, which has been proven by evidence and experience. The more plastic the stone and the larger the plastic radius, the fracture start pressure will decrease more.

Conclusion

The phenomenon of rock fracture is one of the significant issues in the oil industry and plays an important role in processes like well wall stability, slit layer, etc. The goal of this study is to investigate the effect of well characteristics and well inclination on fracture pressure. The rock generally breaks when it is subjected to very high tensions. To describe these fractures, it is assumed that the rock is homogeneous and isotropic (identical properties of Hersu). All sedimentary rocks, except evaporative ones, are fragile under certain conditions. Identifying the fracture areas has a significant role in the exploration, development and production of hydrocarbons, and determination of fracture status plays an important role in well completion operations, hydraulic fractures and selection of the best route for inclinational and horizontal excavation. Well wall fractures include natural fractures and induced fractures (due to drilling operations or slit layer). Induction fractures are caused by the interaction between tensions around the well and fluid pressure inside the well. In-situ tensions, rock strength, pore pressure and fluid pressure inside the well are the effective parameters in the occurrence of fracture in the well wall. Fractures in the well wall are divided into two main groups of shear fractures and tensile fractures without considering the discontinuities in the well wall. In general, in a vertical well, induced tensile fractures are perpendicular to the main minimum tension and in the direction of the main maximum tension, and shear fractures in the direction of the main tension are minimum and perpendicular to the main maximum tension.

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