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Impact of Near-Wellbore Stress in Wellbore Integrity Analysis: Wellbore Fracture Strengthening Approach

Frank Chinedu Ukaeru, Kevin Igwilo, Anthony Chikwe, Obibuike Ubanozie
Federal University of Technology, Owerri,
Department of Petroleum Engineering, Imo State, Nigeria

ABSTRACT

The analysis of borehole stability during drilling is particularly important in the oil and gas industry. Loss of borehole stability during drilling often increases drilling costs, reduces drilling efficiency and even causes the bottom hole to collapse. Regardless of the drilling method used (for example, under-balanced or overbalanced), if borehole is constant throughout the drilling process, drilling integrity problems are unlikely to occur during oil and gas production. The design and implementation of drilling operation is the subject of most research and is a priority for most drilling projects, so it is important to understand the factors that affect borehole stability during drilling. In this study, an analytical model is developed for the purpose of performing quantitative research on the subject of wellbore fortification. The model is appropriate for use with wellbore walls that have small fractures. The development of this model is grounded in the theory of linear elastic fracture mechanics, which functions as the basis for this foundation. The small fracture model does not take into consideration the pressure gradient that exists within the fracture because of the short length of the small fracture. Nevertheless, this model does take into consideration the effect that near-wellbore stress concentration has on the strengthening of the wellbore. The model is validated by comparison to a more basic fracture model that already exists in the research literature.

Keywords: Wellbore, Fracture, Drilling, Drilling fluid, Formation, Model

INTRODUCTION

Because of the complexity of developing hydrocarbon fields, a deeper understanding of the geomechanical behavior of the formations is required. This can include gaining an understanding of fault behavior and large-scale geological features, such as salt diapirs, all the way down to near borehole challenges, such as ensuring the integrity of the drilled borehole wall (Shahbazi et al., 2020). The integrity of the drilled borehole wall due to traction failure, which can result in the loss of drilling fluid and a stuck pipe, or drilling fluid with low mud density, which can result in possible wellbore collapses, is the most important of these considerations. Both mechanisms often prevent further drilling, however, tensile related failures are more common and it has serious impact to the field development (Azim, 2020). The tensile failure intensity increases during the drilling of deep-water basins, or during the design of extreme deviated wells. Some sources, such as wellbore stress concentration, drilling fluid pressure, plastic rock yielding prior to breakouts, swelling of shale formation, fracture due to drilling operation, and intrusion materials used in drilling fluids can all induce some near-wellbore changes. Other sources include plastic rock yielding prior to breakouts, swelling of shale formation, and fracture due to drilling operation. It's possible that the cause is what caused it. Strengthen weak formations (Davies et al., 2013). Evaluating the magnitude of the mechanical change and the radial amplitude helps to optimize the length of the perforated channel and increase the flow rate of near-borehole skin.

In the deep-water basin, the upper area is water, which is much less dense than rocks, thus, it reduces the overall overburden density. As the density of drilling mud varies during the drilling process, the formation can become depleted and the well can stop circulating (Hassanvand et al., 2018). Overall formation stress decreases as pore pressure drops in depleted formations. Also, the danger of losing circulation while drilling through the depleted zone is increased by the presence of slate bearing layers (either above or below the reservoir). It has been stated that there are issues when drilling into depleted reservoirs in both onshore and offshore basins. For instance, deep wells in the Gulf of Mexico face difficulties due to the region's high geostatic and comparatively low compression gradients, resulting in extremely thin margins (Nelson et al., 2005). Reservoir sections in the McAllen and Pharr fields off the Texas coast are sandwiched between highly depleted zones due to the region's complex fault regimes (Montilva et al., 2012). Because of the complex fault regime, predicting pore pressure and fracture slope was challenging.

Subsurface formation breathing (ballooning) in the borehole is a common loss / expansion phenomenon in which the drilling fluid is slowly lost during drilling and then returned when the pump is switched off (Nie et al., 2013). This usually worsens when losses occur in a closed pressure window with complex pore fracture features. The formation ballooning effect is typically caused by the opening and closing of natural fractures, deformation of the drilled borehole, as well as variations in the temperature of the drilling fluid (Zhang et al., 2020). Expansion of formation fracture often occurs in the wellbore when the annular pressure is applied, thus, allowing the fracture to be filled with the mud. When the pressure drops and the fluid returns, the crack closes (Settari and Sen, 2007). Drilling practices in Niger Delta oil/gas fields showed that unexpected drilling difficulties were encountered, such as lost circulation, leaking, differential pressure sticking, and fault seal breach by reactivation. Therefore, the knowledge of pore pressure in depleted reservoir can provide a better understanding of applied Geo-Mechanics and has been increasingly studied. While studies have shown that a decrease in pore pressure correlates with a lessening of horizontal stress orientation, comparatively little attention has been paid to the corresponding shift in fracture gradient.

During geophysical prospecting and development of hydrocarbon well, stresses around the wellbore are key in decision making (Young & Maxwell, 1992). There magnitude and direction are often required to fracturing operations for enhanced production, optimize wellbore stability for directional drilling, and in preventing sand production through proper selective perforation. The orientation and intensity of the three main pressures in the formation define these stresses. Integration of formation mass density from the surface to the subsurface depth of concern typically yields the overburden stress. Correlations with dynamic Poisson's ratio can be used to account for the other two main stresses in the horizontal plane, but literature has shown that this may not be the most reliable approach due to differences in prediction across stratigraphic layers. It is still difficult to predict how much tension will accumulate (Zoback, 2010). Finding a depth of reference with consistent lithology, clay content, temperature, and saturation is essential for correlating measured changes in speed with the corresponding geological changes needed to determine the stress magnitude of a formation from changes in sound velocity. It is necessary to choose a depth range at which the degree uniformity and temperature are quite uniform. Intensity (Biao et al., 2019). Changes in porosity caused by normal compression are due to the corresponding changes in effective volume density and stiffness.

There are many classic issues related to damage in near-wellbore region of rock matrix. However, in many cases it is difficult to quantify the damage to the formation. This is because reservoir engineers cannot take accurate samples and make detailed measurements in areas of interest (Jaeger et al., 2007). Engineers in the oil and gas industry need to have a firm grasp of rock physics and the fundamentals of rock removal. Using principles of Newtonian mechanics, the study of boulders at depth is known as "rock mechanics." The behavior of rocks in reaction to disturbances such as drilling, stress changes, fluid flow, temperature changes, and other physical and chemical phenomena is a prime example of this (ISRM, 2014). Drilling instability, collapse of casings, and borehole failures occur when holes are drilled and completed in stable formations or when finishing fluids are injected into formations that are otherwise stable. Circular holes, which may not be perfectly vertical as shown in Figure 2, cause stress concentrations that can increase the diameter of some of the boreholes. This stress concentration, in contrast to stress in remote areas, can exceed the strength of the formation and lead to fracture (Ajayi & Gupta, 2019). Boreholes can weaken a formation, leading to plasticity and time-related failures, depending on the formation's physical and mechanical characteristics. The formation's integrity can be weakened by completion fluids if the water pressure in the holes is altered (Cao et al., 2015). The formation stress, physical and mechanical qualities determine the severity of these and subsequent drilling failures.

Many different characteristics of natural cracks exist, including morphology, roughness, permeability, connectedness, and deformability. Because of this variation, it is challenging to foresee the frequency and severity of drilling fluid loss when drilling through natural fracture formations (Boyun et al., 2018). The permeability of the fracture and associated characteristics have a major bearing on the loss of circulation. Whether or not a natural fissure results in a loss is dependent on the size of the fissure's opening. The size and shape of fracture openings are affected by both the in-situ stress and the geological history of the region (the origin of the fracture, any prior shear or standard displacement, mineralization, etc.). The roughness of the fracture surface produced by hydraulic openings and asperities regulates the flow of the drilling mud once it has entered the fracture. Fluid movement is channeled and fracture permeability is decreased thanks to asperities (Gray et al., 2009). Particle movement in the fractured zones (such as the transit and deposition of LCMs) is also affected. Predicting how a particle will act after entering a fracture, such as whether or not it will form a seal and where it will form a seal, is essential because of the wide variety of fracture properties. Individual fractures can be identified and their distance estimated using image logs, but information on fracture opening and roughness is rarely accessible, adding another layer of complexity (Kamphuis et al., 1993). The effectiveness of LCMs and other therapies is impacted by these variables.

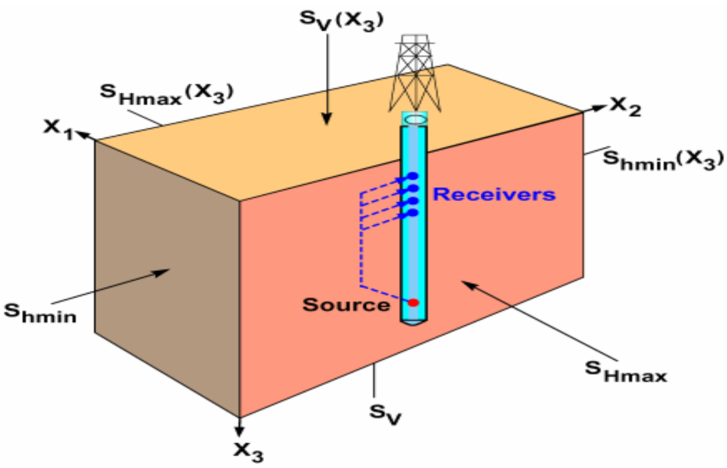

Figure 1. Wellbore Formation Principal Stresses

Reservoir deformation is traditionally simulated according to the theory of linear poroelasticity developed by Biot (1941). Since cracks are the boundaries of the porous elastic region, their deformation also follows the theory of poroelasticity. In its basic form, the deformation of a solid is formed by the equilibrium equation derived from the law of conservation with the linear elastic stress-strain relationship (Zhao et al., 2020). The prediction of fracture extension in existing models is based on Griffith's energy criterion for brittle materials. Therefore, the use of the deformation fracture model in literature assumes that the porous elastic material is brittle and will often not undergo plastic deformation during deformation. According to the Griffith model, crack expansion occurs when the energy available for fracture development is equal to the crack strength (Atkinson & Eftaxiopoulos, 1996). The variational fracture model for reservoir and fracture deformation is based on linear poroelasticity. Fracture simulation not only increase well planning efficiency, but it also provides well integrity information.

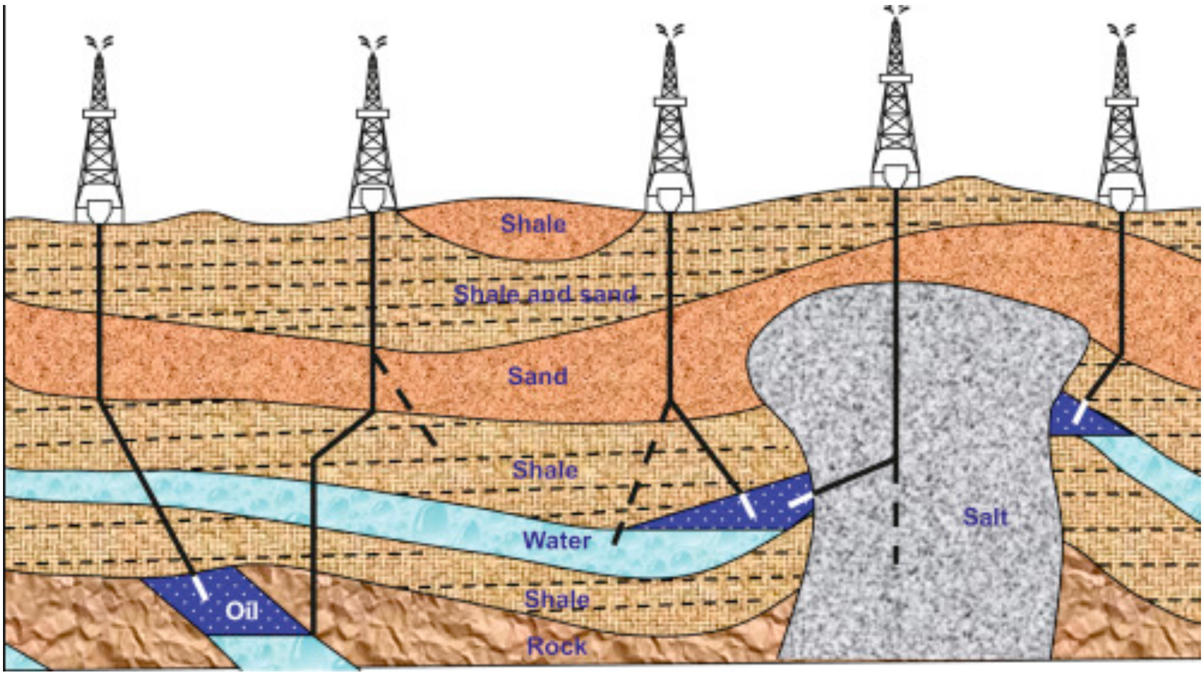

Figure 2. Deviated wells in an Oil and Gas Field

Effectively sealing cracks produced by intentional drilling to improve and increase crack inclination and prolong the operational window is what wellbore strengthening is all about. Well-control accidents could be prevented, borehole integrity could be enhanced, and loss of circulation could be reduced with this device (Richard et al., 2014). Another benefit is that fewer casing threads are needed when drilling a deep well. Drilling reinforcement methods that may be able to handle controls challenges are an essential part of this technology. Linking drilling improvement techniques with business practices can be both economically and environmentally beneficial. This also aids in the design of a drilling program that can get hole section drilled while minimizing the risk for operational hazards. With rapid and consistent production in our brown fields, depletion has become a major challenge in drilling windows especially in scenarios where there is a tight window for well delivery (Shadravan et al., 2015). Nonetheless, Geo-Mechanical modeling of depleted reservoirs is less quantitative without accurate prediction of reservoir stress path, i.e. change of reservoir stresses with pore pressure. This has led to operators incurring continuous and growing non-productive time (NPT).

Drilling stability and borehole strengthening are two of the most important aspects to consider when planning to improve borehole integrity. To date, managing the integrity of the wellbore has been part of the drilling prospect, which uses mechanical equipment (blow out preventer) to control the potential influx of formation fluid (kicks) at unwanted or unscheduled times (Lian et al., 2015). In addition to this problem, when designing borehole integrity, sufficient time and resources should be devoted to the characteristics of the general borehole, especially for borehole stability and strengthening. In a nut shell, borehole integrity means controlling / monitoring down hole pressure in borehole to produce the right hydrocarbon at the right time with non/ minimal non-productive time. The measurement and tracking of hydraulic pressure are crucial for maintaining hydraulic control and ensuring borehole safety (Panjwani et al., 2017). To keep the drilling mud's weight, or the most scientifically equivalent circulation density (ECD), well below the fracture pressure and well above the formation pressure is to keep the mud's hydrostatic pressure constant. It is widely agreed that maintaining drilling integrity requires careful attention to hydraulics (Wang & Taleghani, 2017). Drilling mud pressure (and this includes ECD, annular and friction) must always be below formation pressure and above the fracture pressure range (i.e., the drilling fluid window).

Since the drilling fluid is the first point of contact with the formation, the proper use of certain additives to maintain optimal drilling mud properties is very important for maintaining the ECD in the drilling fluid window (Arlanoglu et al., 2014). Improper handling of the mud properties (mainly ECD) leads to problems related to borehole collapse or sloughing, especially when the ECD is below the pore pressure, and deformation / formation fracturing, when the ECD exceeds the fracture pressure. Insufficient ECD can cause the formations to collapse or sloughing, reducing drilling operation rate of penetration (ROP) and creating an undesirable influx of formation fluids into the borehole (Aston et al., 2007). Excessive ECD can lead to fracturing and loss of circulation, which is a common issue that can affect operator performance.

LITERATURE REVIEW ON WELLBORE CHALLENGES AND RELATED ISSUES

Current challenges in hydrocarbon production include exploring deep reservoirs, which are often involved in very difficult geological features, as well as drilling and completing in various directions, in such formations (Cook et al., 2011). From a geomechanical perspective, the problem of wellbore is often considered separately, mainly due to the difference in scale between these entities. Even when the system is fully operational, the relationship between reservoirs and well analysis is often overlooked. The well is a linear structure and its geomechanical behavior is closely related to the stress state of the rock, the drilling mud system used in drilling, the direction of drilling, pressures and the type of casing (Dupriest, 2005). By the exploration activities, the reservoir rock experiences a significant alteration in its equilibrium composition and configuration due to the effect of hydrocarbon production from the porous medium. These variations in the reservoir stress states is induced by the significant change in the pore pressure. However, the reservoir response to well development is not only concentrated within its boundaries, but also spreads to adjacent rocks, many of which are crossed by wells that cause geomechanical changes. It is clear that there is something called a reservoir-well system, because the behavior of the entities involved is not independent of each other, mainly due to the stress state mentioned (Feng et al., 2015; Feng, 2016).

Formation failure may be due to misunderstandings of borehole stress conditions, drilling practices, inaccessible geomechanical properties or inaccurate interpretations. For maximum long-term output, it is desirable to avoid the uncertainty associated with borehole integrity during drilling (Growcock et al., 2009). The integrity of the well is the determination of the optimal properties and the preparation of the drilling fluid to avoid unwanted or unplanned scenarios during drilling. Loss of part or all of the drilling mud in the formation while drilling an oil or gas well, is encountered when drilling conditions become more difficult, for example, depleted formations, extremely deep-water formations, and also fractured formations. The loss circulation incidents have caused long unproductive time and has increased the costs for drilling (Guo et al., 2014). It has been claimed that circulation loss accounts for over 12% of lost drilling time in the Gulf of Mexico (Wang et al., 2007a). American high-pressure, high-temperature wells spend 10-20% of their budgets on addressing circulatory loss issues (Growcock et al., 2009). There is a $ 2–4 billion yearly estimates put on the global cost of addressing circulation loss issues (Cook et al., 2011). Natural or drilling-induced fracture from the bored borehole to the far field accounts for the vast majority of circulation loss (Feng et al., 2016).

Strengthening boreholes is an efficient method for lowering the amount of circulations that are wasted in fractured formations (Dupriest, 2005; Van Oort et al., 2011). Filling cracks in a borehole with loss circulation material, also known as LCM, is a popular method for reinforcing a borehole. Numerous studies in controlled environments and in the field have demonstrated, either directly or indirectly, that the fracture breakdown pressure can be successfully raised by activities involving borehole strengthening (Guo et al., 2014). These tests are typically expensive and time-consuming, and the information that can be gleaned from the results of the tests is restricted; despite the fact that they are very useful for comprehending the physical fortification of boreholes. There is still a lack of complete comprehension regarding the primary mechanisms responsible for enhancing borehole strengthening.

Borehole reinforcement and strengthening can also be studied using analytical and numerical techniques. Several studies have used computer model approaches to examine borehole strengthening, such as the finite element method (Arlanoglu et al., 2014; Salehi, 2012) and the boundary-element method (Wang et al., 2009). Hoop tension around the borehole can be increased, according to published numerical studies, by bridging the fractures (Arlanoglu et al., 2014; Wang et al., 2009). This demonstrates how challenging it is to extend a fracture after it has been bridged, making it more difficult to accurately predict the breakdown of fracture pressure. In addition, numerical models can be time consuming, limiting the applicability of real-time models. Analytical solutions provide a concise way to explore borehole strengthening. They provide equations that directly show the relationship between fracture pressure breakdown (or fracture width) and various factors such as in-site stress, bridge positions and pore pressure (Van Oort et al., 2014). In addition, the low computational load allows the analytical model to quickly predict fracture pressure and fracture width. This feature allows real time utilization of analytical models' real time for borehole strengthening investigation and drilling fluid property evaluation.

The mechanical linear elastic fracture model for borehole strengthening analysis was created by Abé et al. (1976), and Ito et al. The model can be used to predict where and by how much fracture breakdown pressure will rise after bridging has occurred. However, their suggested model only applies to large fractures that are much larger than the radius of the drilled hole, so it does not take into consideration the effects of stress concentration near the boreholes. Using the one-of-a-kind integrated stress field configuration and the Gauss-Chebyshev polynomial technique, Shahri et al. (2015) suggested a semi-analytical solution for enhancing boreholes using linear elastic fracture engineering. While the borehole effect is addressed in their model, fluid pressure is assumed to be constant within the fracture. This theory holds water for small cracks, but not for large ones where the pressure drop from the flow of viscous fluids can be quite large. The lack of a closed-form solution is another weakness of their approach.

To improve borehole safety, Morita and Fuh (2012) suggested two sets of closed-form solutions. Their model does not take into consideration the influence that boreholes have on the fracture pressure stress factor that is brought about by the pressure of the fluid coming from the bridge at the fracture tip. For this reason, this model is also preferable for use with large fractures, where it is advised that the near-borehole impact be disregarded. For study of borehole fortification, Van Oort et al. (2014) extended the KGD fracture model. Despite the fact that the model accounts for the pressure and width of a fracture after crack sealing, it does not account for the existence of boreholes or pressure drop along the fracture.

In analyzing drilled borehole integrity, it is important to think about how the stress buildup near the borehole affects small fractures in the area of the borehole, and when large fractures stretch far from the borehole, the pressure decrease along the fracture has an impact (Zhong et al., 2017).

METHODOLOGY

A closed analytical model is presented in this part to study small fracture bridges. The model is founded on the superposition principle and linear-elastic fracture mechanics. It can be used to make educated guesses about things like fracture breakdown pressure and fracture breadth before and after bridging.

Analytical Modeling

On the basis of a reasonably straightforward analytical examination of the stress field at the edge of the propagating fracture, the analytical intersection criteria were developed (Renshaw & Pollard, 1995; Gu & Weng, 2010). Renshaw and Pollard (1995) came up with a straightforward test that could determine whether or not a fracture would spread through a friction surface that was perpendicular to the fissure. This criterion is derived from the solution of a linear elastic mechanical fracture for stresses that are located close to the apex of the fracture. Determine the necessary tension to prevent it from sliding along the interface if the stress on the other side of the interface is high enough to cause it to break again. This is the case if the stress on the opposite side of the interface is high enough to cause it to break again. The Renshaw and Pollard cutting conditions are represented mathematically through Equation (1).

$$\frac{\sigma_H}{T_0+\sigma_h} > \frac{0.35+{}^{0.35}/_{\lambda}}{1.06} \tag{1}$$

Where σ_h and σ_H = minimum and maximum horizontal stresses, T_0 = tensile strength of the rock formation, λ = friction coefficient.

Among the most fundamental equations are those that regulate such phenomena as fluid movement, mass retention, fracture deformation, and the propagation and interaction of fractures within a network. Along any node in the fracture network, the following equation describes how mass is conserved (the continuity equation):

$$\frac{\partial q}{\partial s} + \frac{\partial(H_{fl}\bar{w})}{\partial t} + q_L = 0, q_L = 2h_L u_L \tag{2}$$

According to Nejati et al. (2020), identified bedding and foliation in sedimentary rocks as vital factors for the rock properties anisotropy, due to the micro-cracks and constituent minerals preferred orientation. Literature has shown that hydraulic fractures are often adopted for rock mass stimulation to enhance drainage pathways for hydrocarbon reservoirs, and this process is based on Mode I fracture propagation (Figure 3). Thus, knowledge of anisotropic rock crack growth mechanics for Mode 1 is important in analyzing the anisotropic formations (Detournay, 2016). It is also important to study and understand fracture growth theory capability so as to optimally predict possible crack extention in the media of interest.

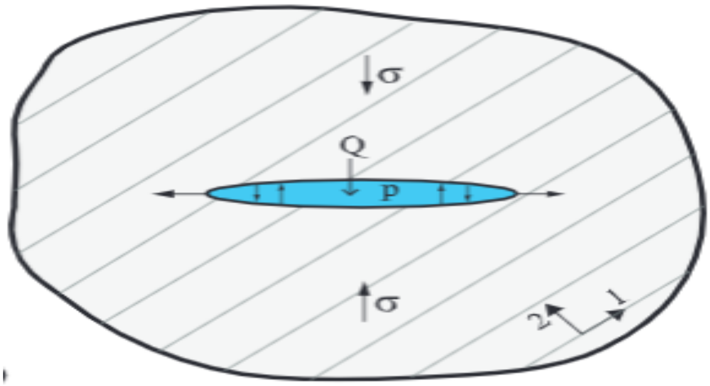

Figure 3. Mode I Crack Tip Loading Condition

Well stability and loss of circulation pressure have both been enhanced through the use of various methods and techniques (Wang et al., 2017, 2020; Yin et al., 2020). It has been determined that one of the most popular technological solutions is to reinforce the wellbore. The formation's integrity and pressure bearing capability will hopefully improve, and the drilling mud window will hopefully grow (Feng et al., 2016). There are two ways to look at wellbore reinforcement: remedial and prophylactic (Feng & Gray, 2017). The preventative method works by enhancing the filter cake made from the drilling fluid by adding special solids (Loss Control Material, or LCM) that inhibit the development of new fractures and the growth of current or induced small fractures. In reality, the probability of fracture growth is decreased when a layer of mud cake with low permeability covers the ground around the borehole (He et al., 2019; Yang et al., 2020). However, once drilling fluid losses have been identified in the formation, corrective measures are taken to either seal the fractures using LCM particles or bridge the gaps using a different material. Here, the LCM particles serve as a barrier at the fracture's tip, stopping fluid pressure from penetrating the fracture surface and causing it to spread (Razavi, 2016; Zhong et al., 2019).

Small Analytical Fracture Model for Wellbore Strengthening

There have been many theories and techniques suggested over the past few decades for bolstering the integrity of boreholes by utilizing fractures. The most common of these techniques are tension caging, fracture closure, and the prevention of further fracture propagation (van Oort et al., 2011; Alberty & Mclean, 2004). By pushing borehole strengthening material into preexisting or developing fractures, this technique demonstrates how to bridge, close, and plug the fracture tip to increase the geological resistance to fracture propagation (Fuh et al., 1992; 2007). The crack propagation resistance model is depicted in a simplified form in Figure 3. To determine why oil-based drilling fluids appear to have lower fracture propagation pressure (FPP) than water-based drilling fluids, JIP developed this technique under the codename DEA-13. While fracture pressure remained constant across all soil types tested, FPP varied significantly. Fracture point screen-out was responsible for this variation. An external filtration cake sealed the crack, limiting the flow of pressure between the drilling fluid system and the severed end of the well. In contrast to the water-based mud system, the oil-based mud system's internal cake filter provides total pressure at the fracture tip and encourages fracture extension with reduced growth pressure (Zhong et al., 2019).

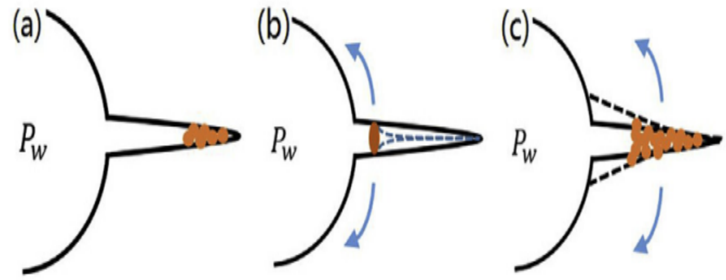

Figure 4. Wellbore Strengthening examples shown in a schematic format. a) Resistance to Crack Propagation, caging for stress as alternative (b). Closure tension of fractures.

According to the research that has been conducted, under linear-elastic conditions, the stress will quickly increase at the zone that is close to the tip of the fracture (r will be less than 0). It is obvious, however, that the level of stress does not increase to an infinite level because the material deforms plastically before achieving its yield strength. This fact explains why the level of stress does not increase to an infinite level. This behavior ultimately results in the development of a plastic zone, the extent of which can frequently be predicted. It is essential to take into account the impact that the different behaviors of plastics can have on formation fractures. Irwin was one of the first people to observe the results, and one of the first things he noticed was that the plastic zone behaved as if the fracture length was longer than it actually was. The orientation of lateral compression in proximity to the fracture plane is yet another essential characteristic of the plastic zone (the neck). The Mohr stress cycle can be used to predict the direction of the neck (González-Velázquez, 2021). This is possible due to the fact that plastic flow always happens along the plane of maximum shear.

The small fracture model that was used in this investigation took into consideration two small fractures that originated from the borehole and extended in the direction of the maximum horizontal load. As a type of case study, plane stress describes this problem perfectly. Borehole fractures are usually bridged at two mirror-image locations during reinforcement. The results of this study define the invasion zone as the portion of the fracture between the borehole wall and the developed bridge, and the non-invasive zone as the remainder of the fracture from the bridge to the fracture point. The distance between the bridge and the fracture's point is thus dependent on the length of the invaded region. The closer the invaded region is, the longer it is. It is expected that the bridge will effectively sever the air flow between the two regions. It is assumed that the pressure at the fracture is the same as the pressure in the borehole before attempting to bridge the breach. This is done keeping in mind that the pressure decrease along the tiny crack is negligible. If the pore pressure of the formation is increased too much, the pressure in the non-intrusion zone (the area that has not been attacked) will be the same. However, after the crack is spanned, the pressure in the intrusion zone (invaded) is the same as the pressure in the borehole. The non-invasive zone will experience a drop-in pressure in real life due to fluid leakage. The stress intensity factor and crack opening breadth can be calculated at the fracture tip using linear elastic fracture mechanics theory. These calculations are based on the assumptions mentioned above.

The net pressure in the non-invaded and invaded zones can be estimated using equations 3.3 and 3.4 respectively.

$$P_{net\_non-inv} = P_p - \sigma_{\theta\theta} \quad (3)$$

$$P_{net\_inv} = P_w - \sigma_{\theta\theta} \quad (4)$$

The net pressure, defined as the differential between the closure pressure and the pressure of the fracturing fluid, is thought to be the mechanism behind the expansion of the fractures in both zones. When the in-situ tension is subtracted from the pressure inside the crack, we get the net pressure. Where $P_{net\_non-inv}$ and P_{net_inv} are the non-invade and invaded zones net pressure respectively; P_w is the pressure in the borehole; P_p is the pore pressure of the formation; and $\sigma_{\theta\theta}$ is the tangential stress of the borehole along the direction of the fracture. $\sigma_{\theta\theta}$ can be estimated approximately with the Kirsch approach, with the assumption that the short fracture under consideration does not affect the borehole stress concentration. Estimation of $\sigma_{\theta\theta}$ is mathematically presented as equation 3.5.

$$\sigma_{\theta\theta} = \frac{1}{2}(\sigma_H + \sigma_h)\left(1 + \frac{{R_w}^2}{{r_c}^2}\right) - \frac{1}{2}(\sigma_H - \sigma_h)\left(1 + 3\frac{{R_w}^4}{{r_c}^4}\right) - P_w\frac{{R_w}^2}{{r_c}^2} \quad (5)$$

Where σ_H *and* σ_h are the horizontal maximum and minimum stresses respectively; R_w and r_c are the borehole radius and distance from the borehole center to the zone along the fracture. The theory of linear elastic fracture mechanics shows that the fracture width can be determined according to the principle of superposition by calculating the following integrals:

$$\delta_\sigma = \int_{R_w}^{D} \frac{8Pnet\_inv}{\pi E'} cosh^{-1}\left(\frac{a}{r_c - R_w}\right) H\left(\frac{r_c - R_w}{a}\right) dr + \int_{D}^{L} \frac{2Pnet\_non-inv}{\pi E'} cosh^{-1}\left(\frac{a}{r_c - R_w}\right) H\left(\frac{r_c - R_w}{a}\right) dr \quad (6)$$

Where L is the length from the fracture tip to the borehole center; D is the distance between the bridge location and the borehole center; δ_σ; a represents the formation fracture length; and E' is the strain modulus of the plane. The relationship between the orientation and the planar strain. The value of Young's modulus was determined by analyzing it as a function of the direction in which the uniaxial tension was applied to the single crystal and the vertical direction of the single crystal to which the constrained must be zero. There are some instances in the physical world in which it is beneficial to employ the idea of plane strain in the context of an elastic theory challenge (Knowles, 2017). The integrals represent the impact of the non-invaded and invaded zones net pressure to the tip width of the fracture respectively. Equations 3.7 and 3.8 can be used to estimate the plane strain modulus and H, respectively.

$$E' = {}^{E}\!/_{(1 - v^2)} \quad (7)$$

$$H\left(\frac{r_c - R_w}{a}\right) = 1.681 - 0.384x\left(\frac{r_c - R_w}{a}\right)^{0.38} \quad (8)$$

Where E and v are the young's modulus and Poisson's ration respectively; and combining equation 3.10 to 3.14 give the mathematical expression for estimating fracture tip width:

$\delta_\sigma = (3\aleph_3 - \aleph_2)\sigma_H - (2\aleph_1 + \aleph_2 + 3\aleph_3)\sigma_h + 2(\aleph_1 + \aleph_2 - \aleph_4)P_w + 2\aleph_4 P_p$ 3.9

Where,

$$\aleph_1 = \int_{R_w}^{L} C_2(r_c)\, dr_c$$

$$\aleph_2 = \int_{R_w}^{L} \frac{{R_w}^2}{{r_c}^2} C_2(r_c)\, dr_c$$

$$\aleph_3 = \int_{R_w}^{L} \frac{{R_w}^4}{{r_c}^4} C_2(r_c)\, dr_c$$

$\aleph_4 = \int_{D}^{L} C_2(r_c)\, dr_c$; and

$$C_2(r_c) = \frac{4}{\pi E'} cosh^{-1}\left(\frac{a}{r_c - R_w}\right)\left\{1.681 - 0.384\left(\frac{r_c - R_w}{a}\right)^{0.38}\right\} \quad (10)$$

Where $\aleph_1$ to $\aleph_4$ are geometry terms derived from the dimensions of the bridge location, borehole fracture system and elastic properties of the formation rock.

Similarly, Feng and Gray (2016) proposed a fracture breakdown pressure model based on superposition and linear elastic fracture mechanics. It can be deduced from this study and Feng and Gray's models that fracture tip width and fracture breakdown pressure models respectively, depends on:

1) Pressure and stress applied to the formation,
2) Bridge location,
3) Formation properties
4) Dimension of the system under investigation.

RESULTS AND DISCUSSION

Model Results for the proposed Small Fractures Model

Table 1 summarizes the primary input data that were used in the development of the minor fracture model. The 6-inch fracture length assumption used by the business is taken into account for the study (Zhong et al., 2017). In each of the sensitivity analyses that are going to follow, the parameters are going to remain the same as they were in Table 1, unless it is specifically mentioned otherwise. The fracture breakdown pressure and the width of the fracture mouth were both calculated with the suggested models, and the results are described below for a variety of load conditions, bridge locations, and rock properties.

Table 1. Input parameters used as a foundation for the proposed model

Parameter	Unit	Value
Wellbore radius (R)	inch	6
Fracture length (a)	inch	6
Minimum horizontal stress (S_{hmin})	psi	3000
Maximum horizontal stress (S_{Hmax})	psi	3600
Wellbore pressure (P_w)	psi	4000
Pore pressure (P_p)	psi	1800
Fracture toughness (K_{IC})	psi-in$^{0.5}$	2000

Different far-field stress anisotropies and bridge positions are displayed alongside the fracture breakdown pressure in Figure 5. By dividing the length of the invaded zone by the length of the fissure, the bridge's location can be pinpointed. This percentage starts at 0 at the fracture's base and rises to 1 at its zenith. The result is the same as if the crack had not been repaired at all if the bridge is placed exactly over it (a ratio of 1). As the maximum principle stress is increased while the minimum principle stress is held at 3000 psi, the stress anisotropy, which is defined as the ratio of the two stresses, rises. This ratio increases by a factor of two when the highest principle stress number is raised by the same factor. As the duration of the invaded zone decreases, the breakdown pressure increases dramatically, as shown in Figure 5 (that is, as the position of the bridge gets closer to the fracture mouth at the wellbore all). Based on these results, bridging the fracture to reinforce the wellbore should be done in the vicinity of the fracture opening. This is true as long as the pressure differentials in front of and behind the bridge are successfully isolated. Figure 5 also shows that the breaking pressure decreases with increasing far-field stress anisotropy. The image provides a visual representation of this pattern. This is because the near-wellbore area experiences less compressive stress when field stress anisotropy is high. Therefore, the fracture needs to be extended at a reduced wellbore pressure. The breakdown pressure is less sensitive to stress anisotropy as the invaded zone length rises, but field stress anisotropy has a smaller impact than bridge location. The breakdown pressure is most sensitive to the position of the bridge.

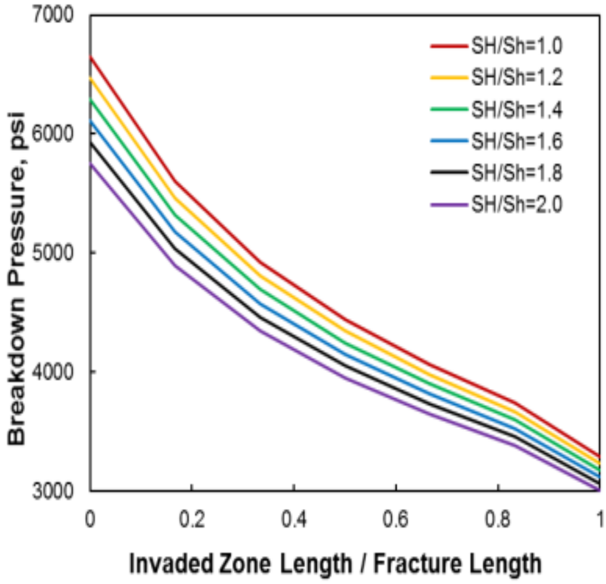

Figure 5. Fracture Breakdown Pressure for various Stress Anisotropies and Bridge Locations

The breakdown pressure for various pore pressures at different bridge positions is shown in Figure 6. The notation for pore pressure variation is the ratio of pore pressure variation to the minimal principle tension, which is held constant at 3000 psi. The findings demonstrate that, for any given pore pressure, the breakdown pressure is equivalent to the minimum principle stress prior to fracture bridging (i.e. the ratio of the length of the invaded zone to the length of the fracture being equal to 1). These findings corroborate those of Ito and colleagues, who (2001).

However, once the fissure has been bridged, the pore pressure has a significant effect on the breakdown pressure. If the pore pressure and minimum principle stress ratio are both raised, the breakdown pressure will decrease. The implications of this discovery for real-world wellbore-strengthening applications are substantial. As was previously mentioned, lost circulation is a common occurrence in two well-known scenarios: drilling through exhausted aquifers and working in overpressured deepwater formations. This is because the formation pressure in the former case is abnormally high, while the field stress produced by the seawater column is comparatively low, resulting in a larger pore pressure and minimum principle stress ratio value.

However, the latter case usually demonstrates a minimum principle stress ratio value and pore pressure that are lower than the former because of pore pressure drop. When applied to depleted reservoirs as opposed to overpressured deepwater formations, wellbore strengthening methods based on bridging the lost circulation cracks are anticipated to produce the results shown in Figure 6.

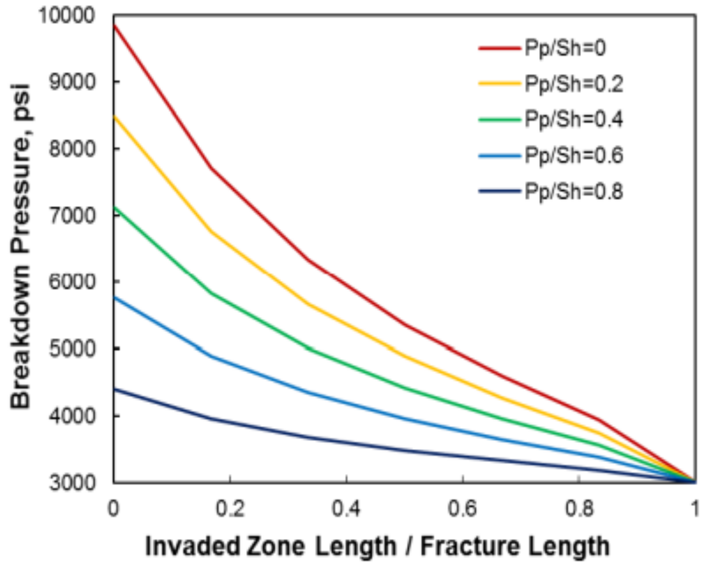

Figure 6. Fracture Breakdown Pressure for varied Pore Pressures and Bridge Locations

Fracture toughness is a measure of how well a substance can resist the spread of a crack once it has started. The ability to withstand fractures is a solid characteristic. The greater the force that must be applied before a material fractures, the higher its fracture toughness. Fracture durability of sedimentary rocks can range from approximately 500 to 2000 psi-in$^{0.5}$ depending on the type of sedimentary rock (Wang, 2007). The breakdown pressure for various fracture toughness can be seen in Figure 7 when compared with a variety of bridge positions. As might be expected, a greater fracture toughness results in a greater breakdown pressure; however, the effect of toughness diminishes with an increase in the invaded zone length.

The PSD of the LCMs needs to be maximized so that the fractures can be effectively bridged during wellbore strengthening operations. One of the most important parameters for LCMs optimization is the fracture breadth, specifically the width of the fracture mouth. LCMs with a PSD D50 that is equal to one third of the fracture opening are considered suitable for bridging lost circulation fractures, according to a rule of thumb in the business (Zhong et al., 2017).

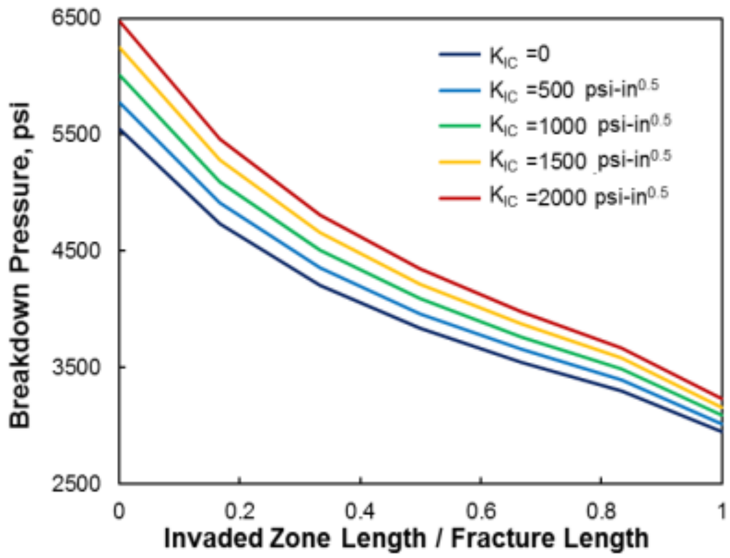

Figure 7. Fracture Breakdown Pressure for various Fracture Toughness and Bridge Locations

Figure 8 depicts the effects of far-field stress anisotropy on fracture mouth width at a variety of bridging locations. For a given value of stress anisotropy, it is clear that a fracture's opening will be as wide as it can get before being bridged (that is, the ratio of the invaded zone length to fracture length is equal to 1). When a bridge is present, the fracture has a propensity to close, as evidenced by a reduction in the width of the fracture mouth after bridging. When bridging a fracture, the bridge's proximity to the wellbore determines how much of a decrease in the fracture mouth width can be attained (that is, if the invaded zone is smaller). Furthermore, as shown in Figure 8, the stress anisotropy greatly affects the size of the crack mouth. Reduced stress anisotropy causes a narrowing of the crack mouth without changing the position of the bridge. After the fracture is bridged near the wellbore, the fracture opening might be able to seal off entirely if the stress anisotropy is low enough.

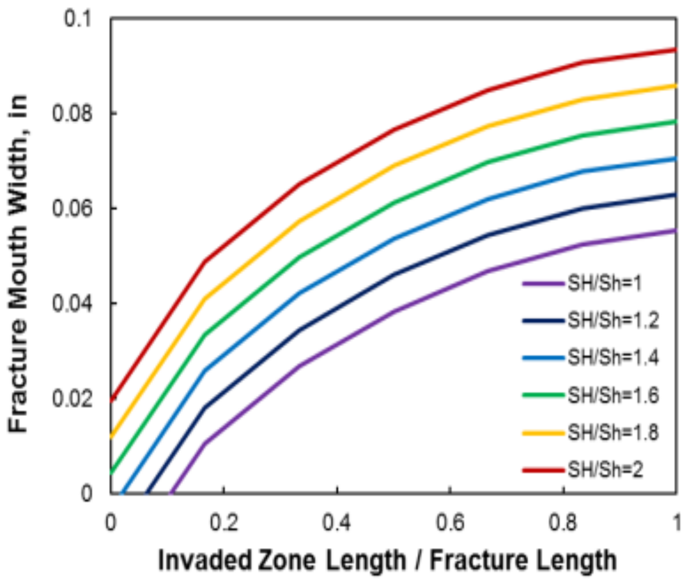

Figure 8. Fracture mouth width for varied stress anisotropies with diverse bridge locations

The fracture width distribution is depicted in Figure 9 for a variety of pore pressures with a number of different bridge positions. It is plain to see that the breadth of the fracture mouth is unaffected by the pore pressure prior to the bridging of the fracture. Following the completion of bridging, the breadth of the fracture mouth will be reduced. A smaller mouth width is the outcome of a smaller pore pressure as well as a lower minimal principle stress ratio. The sensitivity of the fracture mouth width to pore pressure increases as the location of the bridge advances closer to the wellbore wall. After bridging the fracture near the wellbore, the fracture may completely close in cases with relatively lower values for pore pressure and minimum principle stress (for example, pore pressure and minimum principle stress ratio = 0, 0.2, and 0.4). This may occur in situations where the wellbore is under relatively less stress. Even though the fracture is bridged at the fracture mouth, the fracture cannot close because the case has a high pore pressure and a minimal principle stress value of 0.8. The results also confirm the conclusion that was made earlier, which is that the wellbore strengthening operations should be more effective in depleted reservoirs that have a lower pore pressure and minimum principle stress ratio value than in deepwater formations that have a relatively higher pore pressure and minimum principle stress ratio value. This conclusion was made because depleted reservoirs have a lower pore pressure and minimum principle stress ratio value.

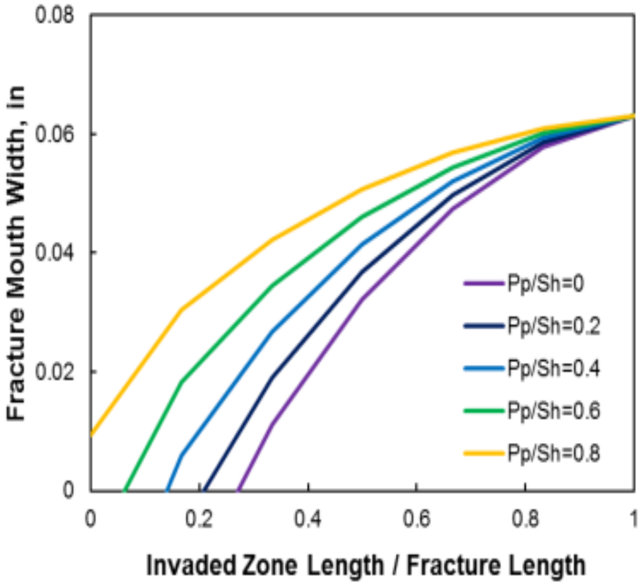

Figure 9. Fracture Mouth Diameter based on varying Pore Pressure and Bridge Location

The elastic properties of the boulder also play a role in determining how wide the fracture mouth will be. In Figures 10 and 11, we see how Young's modulus and Poisson's ratio influence the system. The findings suggest that reducing either the Young's modulus or the Poisson's ratio narrows the crack mouth. However, Young's modulus is more crucial than Poisson's ratio in deciding the width of a fracture mouth. Figure 11 shows that the change in Poisson's ratio only slightly alters the width of the fracture mouth.

Regardless of the values of Young's modulus and Poisson's ratio, another intriguing finding was that the width of the fracture mouth shrank to zero at the same bridge location. This is a thought-provoking realization. The area between the wellbore wall and this crucial bridge site must be bridged for the fracture to close completely. Furthermore, the position of the critical bridge can be identified even when only a limited understanding of the rock's mechanical properties is available. The design of wellbore strengthening systems is significantly affected by this occurrence.

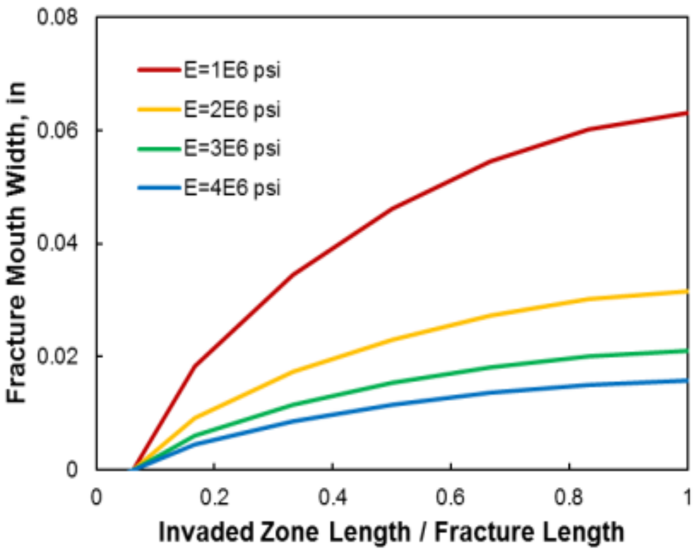

Figure 10. Fracture Mouth Width for varying Young's Modulus at various Bridge Locations

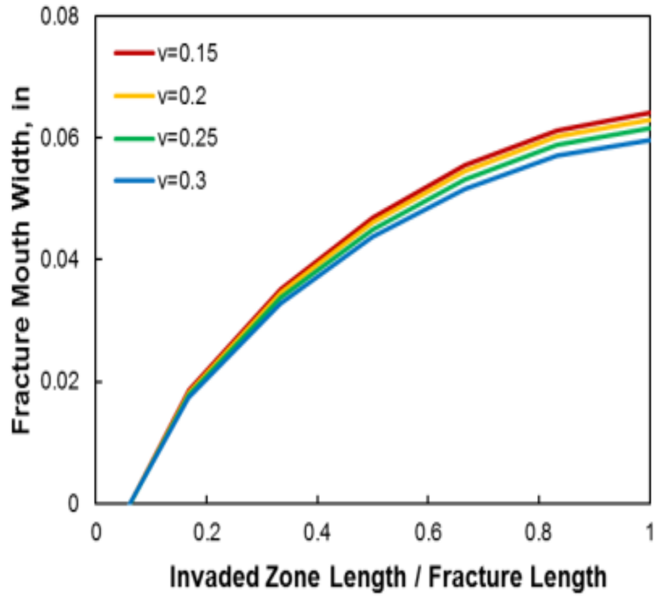

Figure 11. Fracture Mouth Width for numerous Poisson's Ratios and Bridge Locations

CONCLUSION

In the oil and gas business, lost drilling fluids into the formation is a common and costly complication. This may happen because of preexisting cracks on the wellbore wall or as a consequence of drilling operations. As drilling circumstances get tougher, problems like lost circulation—the loss of some or all of the drilling fluid into the formation—are more common. For instance, tapping into ultra-deepwater formations, naturally fractured shale formations, and severely depleted aquifers. Significant amounts of non-productive time (NPT) and expenses have been incurred by the drilling industry as a result of lost circulation events. By performing more wellbore strengthening operations, it is possible to effectively increase the fracture breakdown pressure, also known as the wellbore pressure required to advance the lost circulation fractures. Multiple experiments in controlled environments and in the wild have confirmed this pattern. Due to the fact that these tests are typically very costly and time-consuming to carry out, we have only obtained a limited amount of information from them. Despite the fact that they are very helpful for comprehending the physical aspects of wellbore strengthening, we have only obtained these results. There is still a lot of knowledge gap when it comes to the fundamental principles of wellbore strengthening.

Alternately, numerical and mathematical approaches have been utilized in studies concerning the enhancement of wellbore strength. In order to conduct research into the process of wellbore fortification, computational models that are founded on the finite-element method and the boundary-element method have been put into place. Despite the fact that the published numerical studies show that the hoop tension around a wellbore can be increased by bridging the fractures, it is important to note that this is not always the case. This suggests that the fracture will become more challenging to open and extend as time passes. Therefore, in most cases, it is not possible to accurately predict the fracture breakdown pressure after the fractures have been bridged. In addition, the calculation of the numerical models can take a significant amount of time, which reduces the likelihood that the models will ever be applied in real time. The investigation of wellbore fortification can be streamlined using analytical solutions, which provide a means for doing so. They provide equations that directly demonstrate the relationships between fracture breakdown pressure (or fracture width) and a variety of variables, such as in-situ stresses, bridging locations, and pore pressure. In other words, they show how the two are related. In addition, because they have a minimal computational burden, the analytical models are able to make quick predictions of the fracture breakdown pressure as well as the fracture width. Because of this feature, it is possible to implement analytical models in real time at the rig location for the purpose of evaluating how well the wellbore is holding up and adjusting the mud weight.

The use of specifically engineered particles to bridge fractures in the wellbore wall is the most common approach taken in wellbore strengthening, which is an efficient method for mitigating the effects of this issue. In this study, an analytical model is developed for the purpose of performing quantitative research on the subject of wellbore fortification. The model is appropriate for use with wellbore walls that have small fractures. The development of this model is grounded in the theory of linear elastic fracture mechanics, which functions as the basis for this foundation. The small fracture model does not take into consideration the pressure gradient that exists within the fracture because of the short length of the small fracture. Nevertheless, this model does take into consideration the effect that near-wellbore stress concentration has on the strengthening of the wellbore. The model is validated by comparison to a more basic fracture model that already exists in the research literature.

It can be concluded from this study that:

1. Fractures that are shorter than 2 wellbore radii in length should be modeled using the small fracture model.
2. The model was conceived in the field of linear elastic fracture mechanics and were developed with the principle.
3. The small fracture model takes into account the effect of the stress concentration near the wellbore, but it does not take into account the pressure gradient in the fracture.

RECOMMENDATION

1. For small fractures close to the wellbore, it is crucial to consider the impact of near-wellbore stress concentration when performing a wellbore strengthening study. The result of pressure reduction along the fracture for lengthy, wide cracks that extend far from the well.
2. The fracture breakdown pressure and the width of the fracture mouth can be calculated with the suggested short and large models both before and after bridging the fractures at different sites.

REFERENCES

Ajayi, T., & Gupta, I. (2019). A review of reactive transport modeling in wellbore integrity problems. *Journal of Petroleum Science and Engineering, 175*, 785-803.

Arlanoglu, C., Feng, Y., Podnos, E., Becker, E., & Gray, K. E. (2014). Finite Element Studies of Wellbore Strengthening. Presented at the IADC/SPE Drilling Conference and Exhibition, Society of Petroleum Engineers. https://doi.org/10.2118/168001-MS

Aston, M. S., Alberty, M. W., Duncum, S. D., Bruton, J. R., Friedheim, J. E., Sanders, M. W. (2007). A New Treatment for Wellbore Strengthening in Shale. Presented at the SPE Annual Technical Conference and Exhibition, Society of Petroleum Engineers. https://doi.org/10.2118/110713-MS

Atkinson, C. & Eftaxiopoulos, D. A. (1996). A plane model for the stress field around an inclined, cased and cemented wellbore. *Int. J. Numer. Anal. Methods Geomech., 20*(8), 549-569.

Azim, R. A. (2020). A poroelastic numerical model for simulation of hydraulic fracture propagation: application of Upper Safa Formation-Western Desert-Egypt. *Petroleum Research, 5*(1), 39-51.

Biao, M., Xiaolin, P., Zhengguo, Z., Hao, W., & Wenxin, D. (2019). Laboratory study on core fracturing simulations for wellbore strengthening. *Hindawi Geofluids, 18,* 7942064.

Boyun, G., Liqun, S., & Shuxian, J. (2018). The maximum permissible fracturing pressure in shale gas wells for wellbore cement sheath integrity. *Journal of Natural Gas Science and Engineering, 56,* 324-332.

Cao, P., Karpyn, Z. T., & Li, L. (2015). Self-healing of cement fractures under dynamic flow of CO_2-rich brine. *Water Resour. Res., 51*(6), 4684-4701.

Cook, J., Growcock, F., Guo, Q., Hodder, M., & Van Oort, E. (2011). Stabilizing the wellbore to prevent lost circulation. *Oilfield Rev., 23*, 26–35.

Dupriest, F. E. (2005). Fracture Closure Stress (FCS) and Lost Returns Practices. Presented at the SPE/IADC Drilling Conference, Society of Petroleum Engineers. https://doi.org/10.2118/92192-MS

Feng, Y. (2016). *Fracture Analysis for Lost Circulation and Wellbore Strengthening*. Ph.D. Dissertation, The University of Texas At Austin.

Feng, Y., Arlanoglu, C., Podnos, E., Becker, E., & Gray, K. E. (2015). Finite-Element Studies of Hoop-Stress Enhancement for Wellbore Strengthening. *SPE Drill. Complet., 30*, 38–51. https://doi.org/10.2118/168001-PA

Feng, Y., & Gray, K. E. (2017). Modeling lost circulation through drilling-induced fractures. *SPE J., 20.*

Gray, K. E., Podnos, E., & Becker, E. (2009). Finite-element studies of near-wellbore region during cementing operations: Part 1. *SPE Drilling and Completion Journal, 24,* 127-136.

Growcock, F. B., Kaageson-Loe, N., Friedheim, J., Sanders, M. W., & Bruton, J. (2009). Wellbore Stability, Stabilization and Strengthening. Presented at the Offshore Mediterranean Conference and Exhibition, Offshore Mediterranean Conference.

Gu, H., & Weng, X. (2010). Criterion for fractures crossing frictional interfaces at non-orthogonal angles. In: *44th US Rock Mechanics Symposium and 5th US-Canada Rock Mechanics Symposium*, Salt Lake City, Utah, USA, 27–30 June.

Guo, Q., Cook, J., Way, P., Ji, L., & Friedheim, J. E. (2014). A comprehensive experimental study on wellbore strengthening. IADC/SPE paper 167957 presented at the 2014 IADC/SPE Drilling Conference and Exhibition held in Fort Worth, Texas, USA, March 4-6.

Guo, Q., Cook, J., Way, P., Ji, L., & Friedheim, J. E. (2014). A Comprehensive Experimental Study on Wellbore Strengthening. Presented at the IADC/SPE Drilling Conference and Exhibition, Society of Petroleum Engineers. https://doi.org/10.2118/167957-MS

Hassanvand, M., Moradi, S., Fattahi, M., Zargar, G., & Kamari, M. (2018). Estimation of rock uniaxial compressive strength for an Iranian carbonate oil reservoir: modeling vs. artificial neutral network application. *Petroleum Research, 3*(4), 336-345.

ISRM (2014). The ISRM suggested methods for rock characterization, resting and monitoring 2007-2014. In: Ulusay, R. (Ed.), *The International Society for Rock Mechanics and Rock Engineering* (p. 293). Springer.

Jaeger, J., Cook, N. G., & Robert, Z. (2007). *Fundamentals of Rock Mechanics*. Wiley-Blackwell, p. 489-451.

Kamphuis, H., Davies, D. R., & Roodhart, I. P. (1993). New simulator for the calculation of in-situ temperature profile during well stimulation fracturing treatment. *Int. J. Rock Mech. Min. Sci. Geomech. Abstr., 30*(6), 343.

Lian, Z., Yu, H., Lin, T., & Guo, J. (2015). A study on casing deformation failure during multi-stage hydraulic fracturing for the stimulated reservoir volume of horizontal shale wells. *Journal of Natural Gas Science and Engineering, 23*, 538-546.

Montilva, J., Mota, J., & Billa, R. (2012). Onshore US MPD Use by an Operator. Paper presented at the SPE/IADC Managed Pressure Drilling and Underbalanced Operations Conference and Exhibition, Milan, Italy, March. https://doi.org/10.2118/156909-MS

Nelson, E., Meyer, J., Hillis, R., & Mildren, S. (2005). Transverse drilling-induced tensile fractures in the West Tuna area, Gippsland Basin, Australia: Implications for the in situ stress regime. *International Journal of Rock Mechanics, 42*(3), 361-371.

Nie, X., Zou, C., Pan, L., Huang, Z., & Liu, D. (2013). Fracture analysis and determination of in-situ stress direction from resistivity and acoustic image logs and core data in the Wenchuan Earthquake Fault Scientific Drilling Borehole-2 (50-1370 m). *Tectonophysics, 593*, 161-171.

Panjwani, S., Mcdaniel, J., & Nikolaou, M. (2017). Improvement of zonal isolation in horizontal shale gas wells: a data driven model-based approach. *Journal of Natural Gas Science and Engineering, 47*, 101-113.

Renshaw, C. E., & Pollard, D. D. (1995). An experimentally verified criterion for propagation across unbounded frictional interfaces in brittle, linear elastic-materials. *Int. J. Rock Mech. Min. Sci. Geomech. Abstr., 32*(3), 237– 249.

Richard, J., Davies, S. A., & Robert, S. (2014). Oil and Gas wells and their integrity: implications for shale and unconventional resource exploitation. *Mar. Pet. Geol., 56*, 239-254.

Salehi, S. (2012). *Numerical simulations of fracture propagation and sealing: Implications for wellbore strengthening*. Missouri University of Science and Technology.

Settari, A., & Sen, V. (2007). The role of geomechanics in integrated reservoir modeling. *Lead. Edge, 26*(5), 622-627.

Shadravan, A., Schubert, J., Amani, M., & Teodoriu, C. (2015). Using fatigue-failure envelop for cement-sheath-integrity evaluation. *SPE Drill. Complet., 30*(1), 68-75.

Shahbazi, K., Zarei, A. H., Shahbazi, A., & Tanha, A. A. (2020). Investigation of production depletion rate effect on the near-wellbore stresses in the two Iranian southwest oilfields. *Petroleum Research, 5*, 347-361.

Shahri, M. P., Oar, T. T., Safari, R., Karimi, M., & Mutlu, U. (2015). Advanced Semianalytical Geomechanical Model for Wellbore-Strengthening Applications. *SPE J., 20,* 1276-1286. https://doi.org/10.2118/167976-PA

van Oort, E., & Razavi, O. S. (2014). Wellbore Strengthening and Casing Smear: The Common Underlying Mechanism. Presented at the IADC/SPE Drilling Conference and Exhibition, Society of Petroleum Engineers. https://doi.org/10.2118/168041-MS

Wang, H. (2007). *Near wellbore stress analysis for wellbore strengthening*. University of Wyoming.

Wang, H., Soliman, M. Y., & Towler, B. F. (2009). Investigation of Factors for Strengthening a Wellbore by Propping Fractures. *SPE Drill. Complet., 24,* 441–451. https://doi.org/10.2118/112629-PA

Young, R., & Maxwell, S. (1992). Seismic characterization of a highly stressed rock mass using tomographic imaging and induced seismicity. *J. Geophys. Res.: Solid Earth, 97*(B9), 12361-12373.

Zhang, S., Li, X., & Wang, H. (2020). Experimental study on the geomechanical properties and failure behaviour of interbedded shale during SAGD operation. *Petroleum Research, 6,* 39-51.

Zhao, C., Li, J., Liu, G., & Zhang, X. (2020). Analysis of well stress with the effect of natural fracture nearby wellbore during hydraulic fracturing in shale gas wells. *Journal of Petroleum Science and Engineering, 188*, 106885.

Zhong, R., Miska, S., & Yu, M. (2017a). Modeling of near-wellbore fracturing for wellbore strengthening. *J. Nat. Gas Sci. Eng., 38,* 475–484. https://doi.org/10.1016/j.jngse.2017.01.009

Zoback, M. D. (2010). *Reservoir Geomechanics*. Cambridge University Press, Cambridge.

Nejati, M., Aminzadeh, A., Amann, F., Saar, M. O., & Driesner, T. (2020). Mode I fracture growth in anisotropic rocks: Theory and experiment. *International Journal of Solids and Structures, 195*, 74-90. https://doi.org/10.1016/j.ijsolstr.2020.03.004

Detournay, E. (2016). Mechanics of hydraulic fractures. *Annual Review of Fluid Mechanics, 48*(1), 311-339.

Chong, K. P., Kuruppu, M. D., & Kuszmaul, J. S. (1987). Fracture toughness determination of layered materials. *Eng. Fract. Mech., 28*(1), 43-54.

Wang, Z., & Nielsen, J. Y. C. (2017). Analysis of thermally induced stresses for effective remediation of lost circulation through drilling induced fractures. In: *International Conference on Offshore Mechanics and Arctic Engineering* (Vol. 57762). American Society of Mechanical Engineers. https://asmedigitalcollection.asme.org/OMAE/proceedings-abstract/OMAE2017/57762/V008T11A009/282453

Yin, Q., Yang, J., Li, Z., Huang, Y., Luo, M., Wang, B., Tyagi, M., Xu, G., & Zhao, X. (2020). A field case study of managed pressure drilling in offshore ultra-high-pressure high temperature exploration well in the south China sea. *SPE Drill. Complet., 35*(4), 503–524. https://doi.org/10.2118/191060-PA.

Feng, Y., & Gray, K. E. (2016). A fracture-mechanics-based model for wellbore strengthening applications. *J. Nat. Gas Sci. Eng., 29*, 392–400.

He, W., Hayatdavoudi, A., Chen, K., Sawant, K., Zhang, Q., & Zhang, C. (2019). Enhancement of plastering effect on strengthening wellbore by optimizing particle size distribution of wellbore strengthening materials. *J. Energy Resour. Technol., 141*(12).

Yang, M., Li, M. C., Wu, Q., Growcock, F. B., & Chen, Y. (2020). Experimental study of the impact of filter cakes on the evaluation of LCMs for improved lost circulation preventive treatments. *J. Petrol. Sci. Eng., 191*, 107152. https://doi.org/10.1016/j.petrol.2020.107152

Razavi, S.O. (2016). *Experimental Investigation of the Wellbore Strengthening Phenomenon*. The University of Texas at Austin, USA.

Zhong, R., Miska, S., Yu, M., Meng, M., Ozbayoglu, E., & Takach, N. (2019). Experimental investigation of fracture-based wellbore strengthening using a large-scale true triaxial cell. *Journal of Petroleum Science and Engineering, 178,* 691-699. https://doi.org/10.1016/j.petrol.2019.03.081

González-Velázquez, J. L. (2021). Chapter 2 - Linear elastic fracture mechanics. In J. L. González-Velázquez (Ed.), *A Practical Approach to Fracture Mechanics* (pp. 35-74). Elsevier. https://doi.org/10.1016/B978-0-12-823020-6.00002-5.

Zhong, R., Miska, S., & Yu, M. (2017b). Modeling of near-wellbore fracturing for wellbore strengthening. *J. Nat. Gas Sci. Eng., 38,* 475–484. https://doi.org/10.1016/j.jngse.2017.01.009