Rudarsko-geološko-naftni zbornik	Vol. 19	str. 87 - 98	Zagreb, 2007.

UDC 622.32:622.248
UDK 622.32:622.248

Review
Pregledni rad

Language/Jezik:*English/Engleski*

WELLBORE INSTABILITY: CAUSES AND CONSEQUENCES

NESTABILNOST KANALA BUŠOTINE: UZROCI I POSLJEDICE

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Key words: well, instability, stress

Ključne riječi: bušotina, nestabilnost, naprezanje

Abstract

Wellbore instability is one of the main problems that engineers meet during drilling. The causes of wellbore instability are often classified into either mechanical (for example, failure of the rock around the hole because of high stresses, low rock strength, or inappropriate drilling practice) or chemical effects which arise from damaging interaction between the rock, generally shale, and the drilling fluid. Often, field instances of instability are a result of a combination of both chemical and mechanical. This problem might cause serious complication in well and in some case can lead to expensive operational problems. The increasing demand for wellbore stability analyses during the planning stage of a field arise from economic considerations and the increasing use of deviated, extended reach and horizontal wells.

This paper presents causes, indicators and diagnosing of wellbore instability as well as the wellbore stresses model.

Sažetak

Nestabilnost kanala bušotine jedan je od glavnih problema s kojima se inženjeri susreću tijekom bušenja. Nestabilnost kanala može biti posljedica mehaničkih uzroka (naprimjer, lom stijene oko kanala zbog velikih naprezanja, mala čvrstoća stijene ili neodgovarajuća praksa bušenja) ili kemijskih uzroka (štetne reakcije između stijene, obično šejla i isplake). U praksi je nestabilnost kanala bušotine često posljedica zajedničkog djelovanja kemijskih i mehaničkih mehanizama. Ovaj problem može izazvati ozbiljne komplikacije u bušotini i u nekim slučajevima može dovesti do skupih operativnih problema. Povećana potreba za analizama nestabilnosti kanala bušotine tijekom faze planiranja polja proizlazi iz ekonomskih razmatranja i rastuće upotrebe otklonjenih, povećanog dosega i horizontalnih bušotina.

U radu se prikazuju uzroci i pokazatelji nestabilnosti kanala bušotine, dijagnosticiranje problema te naprezanja u stijeni pribušotinske zone.

Introduction

Unexpected or unknown behavior of rock is often the cause of drilling problems, resulting in an expensive loss of time, sometimes in a loss of part or even whole borehole. Borehole stability is a continuing problem which results in substantial yearly expenditures by the petroleum industry (Bradley, 1978, Awal et al., 2001). As result, a major concern of the drilling engineers is keeping the borehole wall from falling in or breaking down. Detailed attention is paid to drilling fluid programs, casing programs, and operating procedures in drilling a well to minimize these costly problems.

Wellbore instability has become an increasing concern for horizontal and extended reach wells, especially with the move towards completely open hole lateral section, and in some cases, open hole build-up section through shale cap rocks. More recent drilling innovations such as underbalanced drilling techniques, high pressure jet drilling, re-entry horizontal wells and multiple laterals from a single vertical or horizontal well often give rise to challenging wellbore stability question (Martins et al., 1999; Kristiansen, 2004; Tan et al., 2004).

In many cases the section of an optimal strategy to prevent or mitigate the risk of wellbore collapse might compromise one or more of the other elements in the overall well design, e.g., drilling rate of penetration, the risk of differential sticking, hole cleaning ability, or formation damage. For drilling situations it is therefore desirable to apply integrated predictive methods that can, for instance, help to optimize the mud density, chemistry, rheology, the selection of filter cake building additives, and possibly temperature. Sensitivity studies can also help assess if there is any additional risk due to the selected well trajectory and inclination. Wellbore stability predictive models may also be used to design appropriate completions for inflow problems where hole collapse and associated sand production, or even the complete loss of the well, may concerned. For example, in highly permeable and weakly cemented sandstones such predictive tools can be used to decide whether a slotted or perforated liner completion would be preferred over leaving a horizontal well completely open hole (McLellan at all,1994[b]).

Causes of wellbore instability

Wellbore instability is usually caused by a combination of factors which may be broadly classified as being either controllable or uncontrollable (natural) in origin. These factors are shown in **Table 1** (McLellan et al., 1994[a], Bowes and Procter , 1997; Chen et al., 1998; Mohiuddin et al., 2001).

Table 1 Causes of wellbore instability

Tablica 1. *Uzroci nastabilnosti kanala bušotine*

Causes of Wellbore Instability	
Uncontrollable (Natural) Factors	**Controllable Factors**
Naturally Fractured or Faulted Formations	Bottom Hole Pressure (Mud Density)
Tectonically Stressed Formations	Well Inclination and Azimuth
High In-situ Stresses	Transient Pore Pressures
Mobile Formations	Physico/chemical Rock-Fluid Interaction
Unconsolidated Formations	Drill String Vibrations
Naturally Over-Pressured Shale Collapse	Erosion
Induced Over-Pressured Shale Collapse	Temperature

Uncontrollable factors

Naturally fractured or faulted formations

A natural fracture system in the rock can often be found near faults. Rock near faults can be broken into large or small pieces. If they are loose they can fall into the wellbore and jam the string in the hole (Nguyen et al., 2007). Even if the pieces are bonded together, impacts from the BHA due to drill string vibrations can cause the formation to fall into the wellbore. This type of sticking is particularly unusual in that stuck pipe can occur while drilling. **Figure 1** shows possible problems as result drilling a naturally fractured or faulted system. This mechanism can occur in tectonically active zones, in prognosed fractured limestone, and as the formation is drilled. Drill string vibration have to be minimized to help stabilize these formations (Bowes and Procter, 1997).

Hole collapse problems may become quite severe if weak bedding planes intersect a wellbore at unfavorable angles. Such fractures in shales may provide a pathway for mud or fluid invasion that can lead to time-depended strength degradation, softening and ultimately to hole collapse. The relationship between hole size and the fracture spacing will be important in such formations.

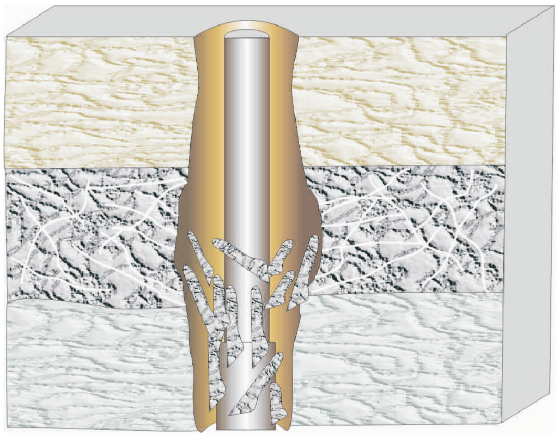


Figure 1 Drilling through naturally fractured or faulted formations

Slika 1. *Bušenje kroz prirodno raspucane ili rasjedima ispresjecane formacije*

Tectonically Stressed Formations

Wellbore instability is caused when highly stressed formations are drilled and if exists a significant difference between the near wellbore stress and the restraining pressure provided by the drilling fluid density. Tectonic stresses build up in areas where rock is being compressed or stretched due movement of the earth´s crust. The rock in these areas is being buckled by the pressure of the moving tectonic plates.

When a hole is drilled in an area of high tectonic stresses the rock around the wellbore will collapse into the wellbore and produce splintery cavings similar to those produced by over-pressured shale (**Figure 2**). In the tectonic stress case the hydrostatic pressure required to stabilize the wellbore may be much higher than the fracture pressure of the other exposed formations (Bowes and Procter, 1997). This mechanism usually occurs in or near mountainous regions. Planning to case off these formations as quickly as possible and maintaining adequate drilling fluid weight can help to stabilize these formations

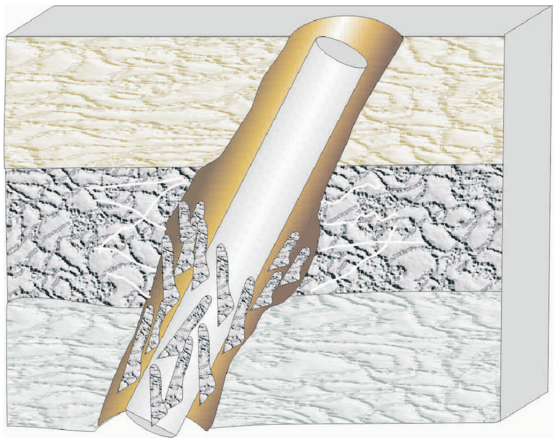


Figure 2 Drilling through tectonically stressed formations

Slika 2. *Bušenje kroz tektonski napregnute formacije*

High in-situ stresses

Anomaliously height in-situ stresses, such as may be found in the vicinity of salt domes, near faults, or in the inner limbs of a folds may give rise to wellbore instability. Stress concentrations may also occur in particularly stiff rocks such as quartzose sandstones or conglomerates. Only a few case histories have been described in the literature for drilling problems caused by local stress concentrations, mainly because of the difficulty in measuring or estimating such in situ stresses.

Mobile formations

The mobile formation squeezes into the wellbore because it is being compressed by the overburden forces. Mobile formations behave in a plastic manner, deforming under pressure. The deformation results in a decrease in the wellbore size, causing problems of running BHA´s, logging tools and casing (**Figure 3**). A deformation occurs because the mud weight is not sufficient to prevent the formation squeezing into the wellbore (Bowes and Procter, 1997). This mechanism normally occurs while drilling salt. An appropriate drilling fluid and maintaining sufficient drilling fluid weight are required to help stabilize these formations.

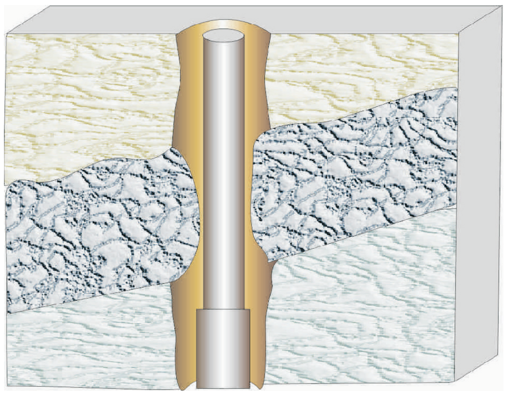


Figure 3 Drilling through mobile formations

Slika 3. *Bušenje kroz pokretljive formacije*

Unconsolidated formations

An unconsolidated formation falls into the wellbore because it is loosely packed with little or no bonding between particles, pebbles or boulders. The collapse of formations is caused by removing the supporting rock as the well is drilled (**Figure 4**). It happens in a wellbore when little or no filter cake is present. The un-bonded formation (sand, gravel, etc.) cannot be supported by hydrostatic overbalance as the fluid simply flows into the formations. Sand or gravel then falls into the hole and packs off the drill string. The effect can be a gradual increase in drag over a number of meters, or can be sudden (Bowes and Procter, 1997). This mechanism is normally associated with shallow formation. An adequate filter cake is required to help stabilize these formations.

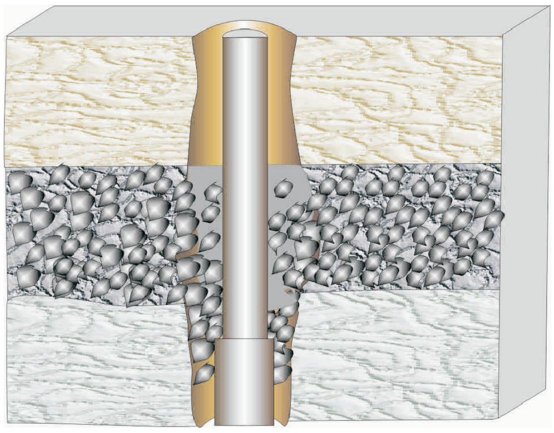


Figure 4 Drilling through unconsolidated formations

Slika 4. *Bušenje kroz nekonsolidirane formacije*

Naturally Over-Pressured Shale Collapse

Naturally over-pressured shale is the one with a natural pore pressure greater than the normal hydrostatic pressure gradient. Naturally over-pressured shales are most commonly caused by geological phenomena such as under-compaction, naturally removed overburden and uplift (**Figure 5**). Using insufficient mud weight in these formations will cause the hole to become unstable and collapse (Bowes and Procter, 1997; Tan et al., 1997). This mechanism normally occurs in prognosed rapid depositional shale sequences. The short time hole exposure and an adequate drilling fluid weight can help to stabilize these formations.

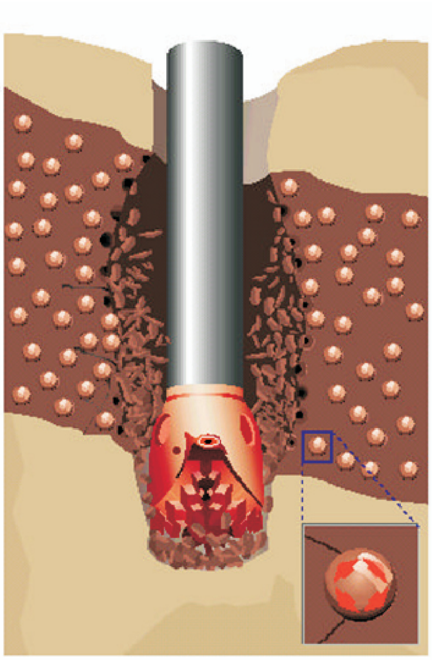


Figure 5 Drilling through a naturally over-pressured shale

Slika 5. *Bušenje kroz šejl pod prirodnim nadtlakom*

Induced Over-Pressured Shale Collapse

Induced over-pressured shale collapse occurs when the shale assumes the hydrostatic pressure of the wellbore fluids after a number of days exposures to that pressure. When this is followed by no increase or a reduction in hydrostatic pressure in the wellbore, the shale, which now has a higher internal pressure than the wellbore, collapses in a similar manner to naturally over-pressured shale (**Figure 6**) (Bowes and Procter, 1997). This mechanism normally occurs in water based drilling fluids, after a reduction in drilling fluid weight or after a long exposure time during which the drilling fluid was unchanged.

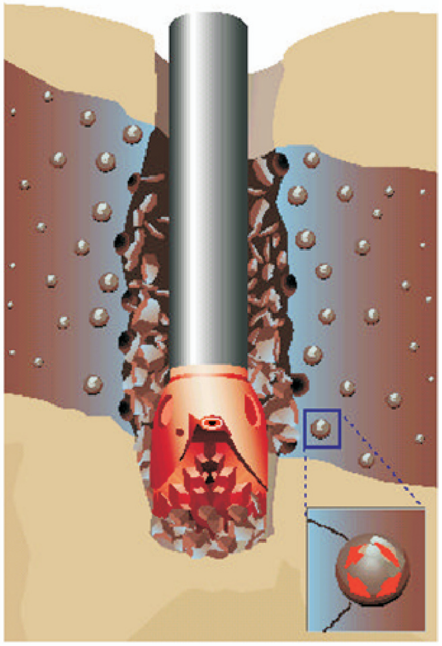


Figure 6 Drilling through induced over-pressured shale

Slika 6. *Bušenje kroz šejl pod izazvanim nadtlakom*

Controllable factors

Bottom hole pressure (mud density)

Depending upon the application, either the bottom hole pressure, the mud density or the equivalent circulating density (ECD), is usually the most important determinant of whether an open wellbore is stable (**Figures 7 and 8**) (Hawks and McLellan, 1997; Gaurina-Međimurec, 1998). The supporting pressure offered by the static or dynamic fluid pressure during either drilling, stimulating, working over or producing of a well, will determine the stress concentration present in the near wellbore vicinity. Because rock failure is dependent on the effective stress the consequence for stability is highly dependent on whether and how rapidly fluid pressure penetrate the wellbore wall. That is not to say however, that high mud densities or bottom hole pressures are always optimal for avoiding instability in a given well. In the absence of an efficient filter cake, such as in fractured formations, a rise in a bottom hole pressure may be detrimental to stability and can compromise other criteria, e.g., formation damage, differential sticking risk, mud properties, or hydraulics (Tan and Willoughby, 1993; McLellan, 1994[a]; Mohiuddin et al., 2001).

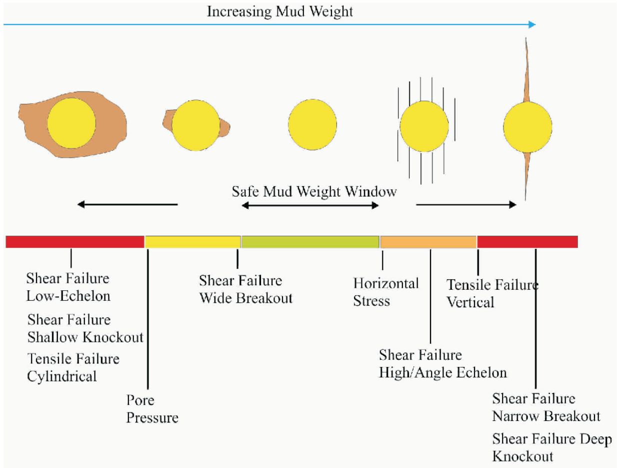


Figure 7 Effect of mud weight on the stress in wellbore wall

Slika 7. *Utjecaj gustoće isplake na naprezanja u kanalu bušotine*

Well Inclination and Azimuth

Inclination and azimuthal orientation of a well with respect to the principal in-situ stresses can be an important factor affecting the risk of collapse and/or fracture breakdown occurring (**Figure 8**). This is particularly true for estimating the fracture breakdown pressure in tectonically stressed regions where there is strong stress anisotropy (McLellan, 1994[a]).

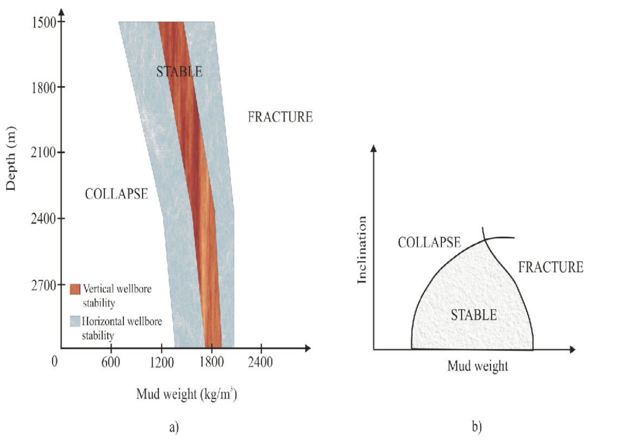


Figure 8 Effect of the well depth (a) and the hole inclination (b) on wellbore stability

Slika 8. *Utjecaj dubine (a) i otklona (b) na stabilnost kanala bušotine*

Transient wellbore pressures

Transient wellbore pressures, such as swab and surge effects during drilling, may cause wellbore enlargement (Hawks and McLellan, 1997). Tensile spalling can occur when the wellbore pressure across an interval is rapidly reduced by the swabbing action of the drill string for instance. If the formation has a sufficiently low tensile strength or is pre-fractured, the imbalance between the pore pressures in the rock and the wellbore can literally pull loose rock off the wall. Surge pressures can also cause rapid pore pressures increases in the near-wellbore area sometimes causing an immediate loss in rock strength which may ultimately lead to collapse. Other pore pressure penetration-related phenomena may help to initially stabilize wellbores, e.g. filter cake efficiency in permeable formations, capillary threshold pressures for oil-based muds and transient pore pressure penetration effects (McLellan, 1994[a]).

Physical/chemical fluid-rock interaction

There are many physical/chemical fluid-rock interaction phenomena which modify the near-wellbore rock strength or stress. These include hydration, osmotic pressures, swelling, rock softening and strength changes, and dispersion. The significance of these effects depend on a complex interaction of many factors including the nature of the formation (mineralogy, stiffness, strength, pore water composition, stress history, temperature), the presence of a filter cake or permeability barrier is present, the properties and chemical composition of the wellbore fluid, and the extent of any damage near the wellbore (McLellan, 1994[a]).

Drillstring vibrations (during drilling)

Drillstring vibrations can enlarge holes in some circumstances. Optimal bottomhole assembly (BHA) design with respect to the hole geometry, inclination, and formations to be drilled can sometimes eliminate this potential contribution to wellbore collapse. Some authors claim that hole erosion may be caused due to a too high annular circulating velocity. This may be most significant in a yielded formation, a naturally fractured formation, or an unconsolidated or soft, dispersive sediment. The problem may be difficult to diagnose and fix in an inclined or horizontal well where high circulating rates are often desirable to ensure adequate hole cleaning (McLellan, 1994[a]).

Drilling fluid temperature

Drilling fluid temperatures, and to some extent, bottomhole producing temperatures can give rise to thermal concentration or expansion stresses which may be detrimental to wellbore stability. The reduced mud temperature causes a reduction in the near-wellbore stress concentration, thus preventing the stresses in the rock from reaching their limiting strength (McLellan, 1994[a]).

Indicators of wellbore instability

A list of the indicators of wellbore instability which are primarily caused by wellbore collapse or convergence during the drilling, completion or production of a well is shown in **Table 2**. They are classified in two groups: direct and indirect causes. Direct symptoms of instability include observations of overgauge or undergauge hole, as readily observed from caliper logs (Mohiuddin et al., 2001). Caving from the wellbore wall, circulated to surface, and hole fill after tripping confirm that spalling processes are occurring in the wellbore. Large volumes of cuttings and/or cavings, in excess of the volume of rock which would have been excavated in a gauge hole, similarly attest to hole enlargement. Provided the fracture gradient was not exceeded and vuggy or naturally fractured formations were not encountered, a requirement for a cement volume in excess of the calculated drilled hole volume is also a direct indication that enlargement has occurred (McLellan et al., 1994[a]).

Table 2 Indicators of wellbore instability

Tablica 2. *Pokazatelji nestabilnosti kanala bušotine*

Indicators of wellbore instability	
Direct indicators	**Indirect indicators**
Oversize hole	High torque and drag (friction)
Undergauge hole	Hanging up of drillstring, casing, or coiled tubing
Excessive volume of cuttings	Increased circulating pressures
Excessive volume of cavings	Stuck pipe
Cavings at surface	Excessive drillstring vibrations
Hole fill after tripping	Drillstring failure
Excess cement volume required	Deviation control problems
	Inability to run logs
	Poor logging response
	Annular gas leakage due to poor cement job
	Keyhole seating
	Excessive doglegs

Diagnosing of wellbore instability mechanisms

Diagnosing the four most important wellbore instability mechanisams is described in **Figure 9**. Three of these are mechanical (breakouts, closely spaced natural fractures and weak planes, drilling induced fractures) and one of these is chemical (chemical activity) in origin.

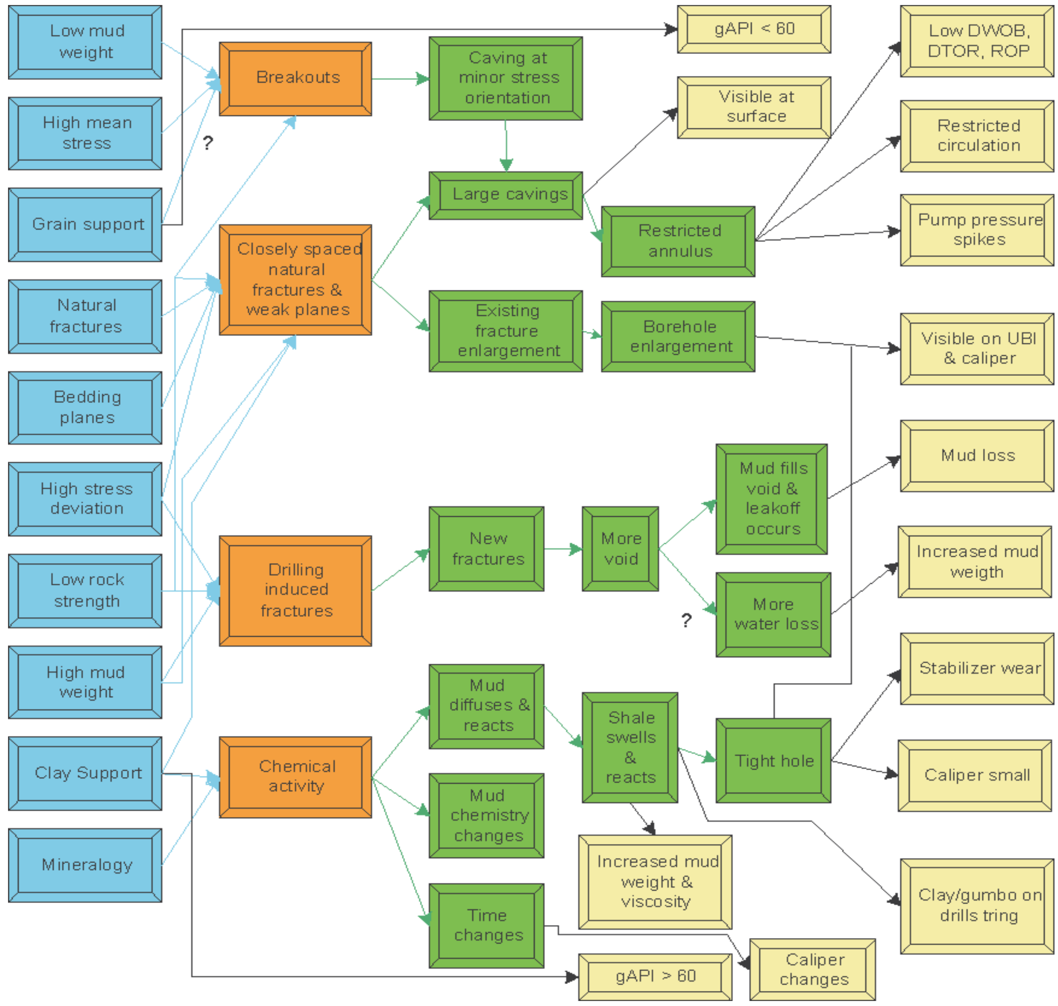


Figure 9 Diagnosing the 4 most common wellbore instability mechanisms

Slika 9. *Dijagnostciranje četiri najčešća mehanizma nestabilnosti kanala*

Wellbore stresses – model development

Before describing the variety of predictive models that are available for assessing wellbore stability it is necessary to define what constitutes the ″failure″ of a wellbore. Clearly, the spalling or erosion of manageable amounts of rock from a wellbore wall does not necessarily imply that the wellbore has failed. Providing that sufficient hydraulic power is available to circulate cavings out of the hole it cannot be claimed that hole enlargement, or convergence in many cases, has impaired the ability of the hole to serve its engineering function that is – to gain access to subsurface hydrocarbons. It follows, therefore, that wall deformation and yielding phenomena do not necessarily mean that a wellbore has ″failed″ (McLellan, 1994[a]).

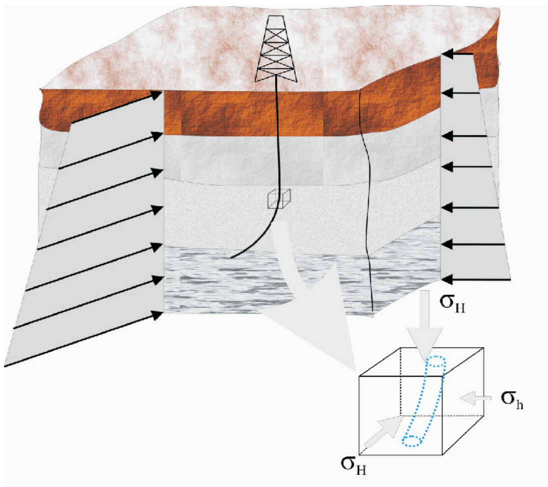


Figure 10 In-situ stresses

Slika 10. *In-situ naprezanja*

Before a wellbore is drilled the rock is in a state of equilibrium. The stresses in the earth under these conditions are known as the far field stresses (σ_v, σ_H, σ_h or in-situ stresses (Gaurina-Međimurec, 1994). When the well is drilled, the rock stresses in the vicinity of the wellbore are redistributed as the support originally offered by the drilled out rock is replaced by the hydraulic pressure of the mud. The stresses can be resolved into a vertical or overburden stress, σ_v, and two horizontal stresses, σ_H (the maximum horizontal in-situ stress), and σ_h (the minimum horizontal in-situ stress), which are generally unequal (**Figure 10**) (McLean et al.,1990).

If the redistributed stress state exceeds the rock strength, either in tension or compression, then instability may result. **Figure 11** shows the wellbore stresses after drilling. These are described as radial stress σ_r, tangential stress (circumferential or hoop stress) σ_t , and axial stress σ_a. The radial stress acts in all directions perpendicular to the wellbore wall, the tangential stress circles the borehole, and the axial stress acts parallel to the wellbore axis (McLean, 1990).

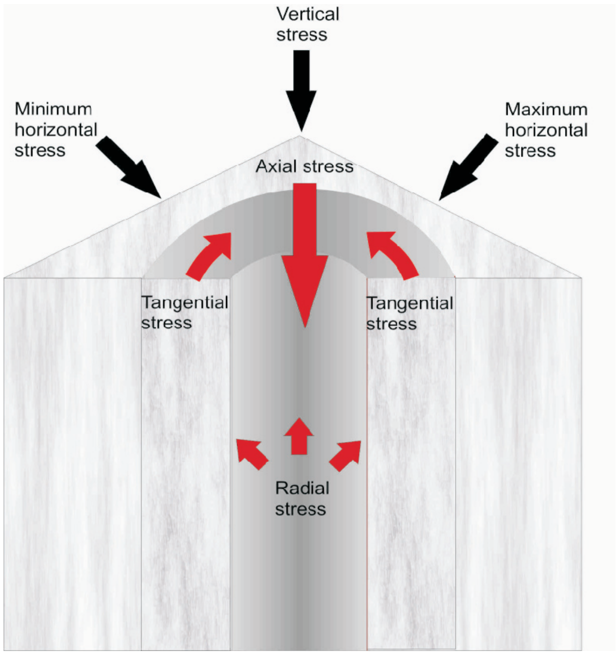


Figure 11 Wellbore stresses

Slika 11. *Naprezanja u kanalu bušotine*

The local stress distribution around a wellbore are controlled by mechanical (in-situ stresses), chemical, thermal, and hydraulic effects. The coordinate referencing system used to calculate the stress distribution around a wellbore, governed by the in-situ stress and hydraulic effects, is shown in **Figure 12**.

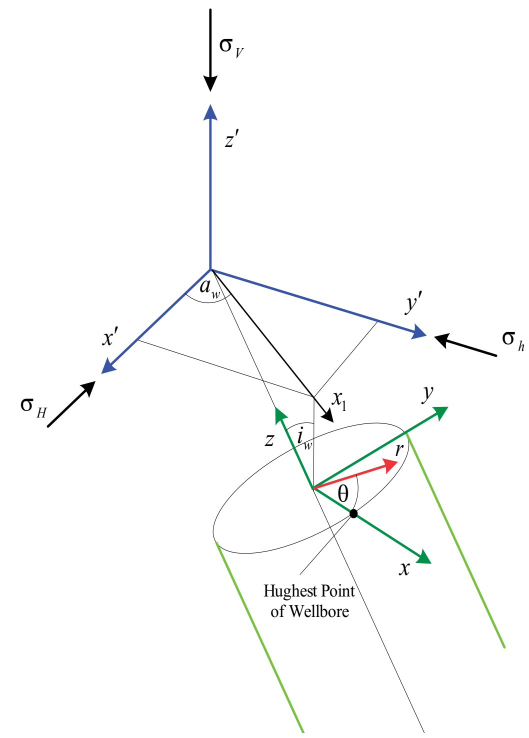


Figure 12 The coordinate system for the in-situ stress display

Slika 12. *Koordinatni sustav za prikaz in-situ naprezanja*

Local stresses induced by in-situ stress and hydraulic effects at the wellbore wall ($r = r_w$), for vertical well can be described as follows:

$$\begin{aligned}
\sigma_r &= p_w \\
\sigma_t &= (\sigma_x + \sigma_y) - (\sigma_x - \sigma_h) \cdot \cos 2\theta - p_w \\
\sigma_a &= \sigma_z - 2(\sigma_x - \sigma_y) \nu \cdot \cos 2\theta
\end{aligned} \qquad \text{(Eq. 1)}$$

According to previous equations it can be concluded that the radial stress σ_r depends on the wellbore pressure or mud weight. The tangential stress σ_t depends on σ_t, σ_t, p_w and θ. The wellbore stresses diminish rapidly from the borehole wall converting to far field stresses because away from the wellbore the rock is in an undisturbed state.

Local stresses induced by in-situ stress and hydraulic effects at the wellbore wall ($r = r_w$), for deviated and horizontal wells, well can be expressed by Eq. 2:

$$\begin{aligned}
\sigma_r &= p_w \\
\sigma_t &= (\sigma_x + \sigma_y) - 2 \cdot (\sigma_x - \sigma_y) \cdot \cos 2\theta - 4\tau_{xy} \cdot \sin 2\theta - P_w \\
\sigma_a &= \sigma_z - \nu \cdot [2 \cdot (\sigma_x - \sigma_y) \cdot \cos 2\theta + 4\tau_{xy} \cdot \sin 2\theta] \\
\tau_{\theta z} &= 2 \cdot (\tau_{yz} \cdot \cos\theta - \tau_{xz} \cdot \sin\theta) \\
\tau_{r\theta} &= \tau_{rz} = 0
\end{aligned} \qquad \text{(Eq.2)}$$

Local Stresses at the wellbore wall ($r = r_w$) induced by chemical and thermal effects can be expressed as follows (Eq.3):

$$\sigma_r = 0$$
$$\sigma_t = \frac{\alpha_p \cdot (1-2\nu)}{1-\nu} \cdot (P_w - P_i) + \frac{E \cdot \alpha_t}{3 \cdot (1-\nu)} \cdot (T_w - T_i)$$
$$\sigma_a = \frac{\alpha_p \cdot (1-2\nu)}{1-\nu} \cdot (P_w - P_i) + \frac{E\alpha_t}{3 \cdot (1-\nu)} (T_w - T_i) \qquad \text{(Eq.3)}$$

From Equation 3, one notes that pore pressure and temperature profiles are needed to calculate the stress distribution around a wellbore arising from chemical and thermal effects. The pore pressure profile is altered by water and ion movements into or out of the shale due to hydraulic, chemical, and electical potentials. Pore pressure and temperature profiles can be obtained by using equations presented in literature (Ottesen and Kwakwa, 1991; Lomba et al, 2000; Awal et al., 2001; Zhang et al, 2006; Nguyen et al., 2007).

In order to evaluate the potential for wellbore stability a realistic constitutive model must be used to compute the stresses and/or strains around the wellbore. The computed stresses and strains must then be compared against a given failure criterion.

Shear Failure

Numerous shear failure criteria such as Mohr-Coulomb, Drucker-Prager, von Mises, modified Lade criteria and others are proposed in the literature (Simangunsong et al., 2006; Zhang et al, 2006; Maury et al., 1987; Morita et al., 1993; McLean et al., 1990).

The Mohr-Coulomb shear-failure model is one of the most wiedely used models for evaluating borehole collapse. This model neglects the intermediate principal stress but includes the effect of directional strengths of shales. The shear-failure criterion can be expressed by the following (Eq.4):

$$(\sigma_1 - \alpha_p \cdot P_p) \leq C_o + (\sigma_3 - \alpha_p \cdot P_p) \cdot \tan^2\varphi \qquad \text{(Eq. 4)}$$

Shear Stress magnitudes can be ordered in 6 different ways, as shown in **Table 3** (Bowes and Procter, 1997).

Table 3 Shear failure types

Tablica 3. *Tipovi smičnog loma*

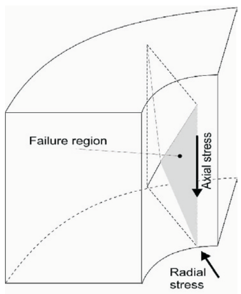
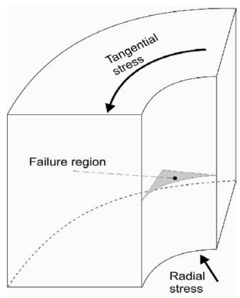
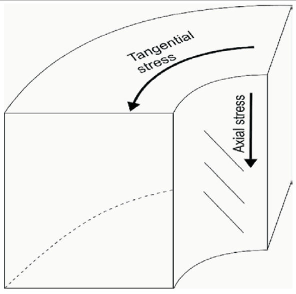
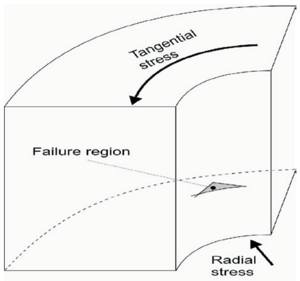
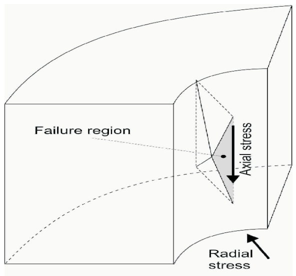
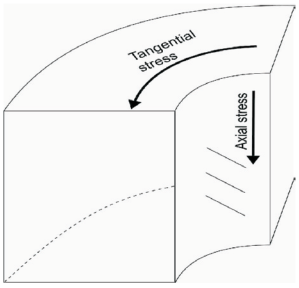
Failure type	Geometry and Orientation	Figure
Shear Failure Shallow Knockout $\sigma_a > \sigma_t > \sigma_r$	The failure will occure in the radial/axial plane because the maximum (σ_a) and minimum (σ_r) stresses are oriented in this plane (a vertical plane).	
Shear Failure Wide Breakout $\sigma_t > \sigma_a > \sigma_r$	The failure will occure in the radial/tangential plane because the maximum (σ_t) and minimum (σ_r) stresses are oriented in this plane (the horizontal plane).	

Table 3 Shear failure types (continued)

Tablica 3. *Tipovi smičnog loma (nastavak)*

<table>
<tr><th>Failure type</th><th>Geometry and Orientation</th><th>Figure</th></tr>
<tr><td>Shear Failure High-Angle Echelon
$\sigma_a > \sigma_r > \sigma_t$</td><td>The failure will occure in the axial/tangential arc because the maximum (σ_a) and minimum (σ_t) stresses are oriented in this arc (the arc of the borehole wall).</td><td>
</td></tr>
<tr><td>Shear Failure Narrow Breakout
$\sigma_r > \sigma_a > \sigma_t$</td><td>The failure will occure in the radial/tangential plane because the maximum (σ_r) and minimum (σ_t) stresses are oriented in this plane (the horizontal plane).</td><td>
</td></tr>
<tr><td>Shear Failure Deep Knockout
$\sigma_r > \sigma_t > \sigma_a$</td><td>The failure will occure in the radial/axial plane because the maximum (σ_r) and minimum (σ_a) stresses are oriented in this plane (a vertical plane).</td><td>
</td></tr>
<tr><td>Shear Failure Low-Angle Echelon
$\sigma_t > \sigma_r > \sigma_a$</td><td>The failure will occure in the axial/tangential arc because the maximum (σ_t) and minimum (σ_a) stresses are oriented in this arc (the arc of the borehole wall).</td><td>
</td></tr>
</table>

Tensile Failure

Tensile failure occurs when the stress imposed by drilling mud exceeds the tensile strength of formations (T_o). The extremely excessive weight of drilling mud creates hydraulic fracture, which triggers massive circulation loss and matrix deformation. Hence, this failure becomes the upper limit of the mud density window in safe drilling practice.

Tensile failure usually occurs when the least effective principal stress surpasses the formation rock tensile strength. Mathematically this criterion can be expressed as follows (Simangunsong et al., 2006; Zhang et al, 2006) :

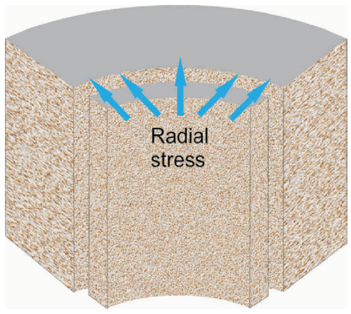
$$\sigma_3 - P_p \le T_o \qquad \text{(Eq. 5)}$$

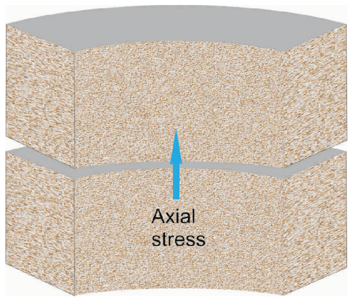
The tensile strength of the rock can be assumed to be equal to zero because, theoretically, a fracture initiates in a flaw, a joint, or an existing fracture. To apply the criteria in Eq. 5 all principal stresses are subject to tensor transformations (Simangunsong at al., 2006). Tensile stress magnitudes can be ordered in 3 different ways, as shown in **Table 4** (Bowes and Procter, 1997).

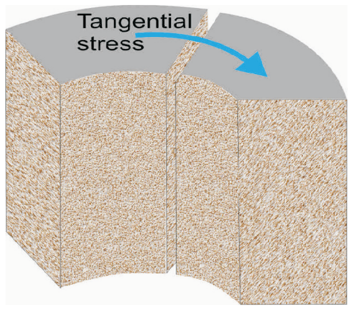
Table 4 Tensile failure types

Tablica 4. *Tipovi vlačnog loma*

<table>
<tr><th>Failure type</th><th>Geometry and Orientation</th><th>Figure</th></tr>
<tr><td>Tensile Failure Cylindrical

$\sigma_r \leq -T_o$</td><td>This failure is concentric with the borehole. A low mud weight would favor the failure due to the magnitude of σ_r being lower.</td><td>
</td></tr>
<tr><td></td><td></td><td></td></tr>
<tr><td>Tensile Failure Horizontal

$\sigma_a \leq -T_o$</td><td>This failure creates horizontal fractures.</td><td>
</td></tr>
<tr><td>Tensile Failure Vertical

$\sigma_t \leq -T_o$</td><td>This failure creates a vertical fracture parallel with the maximum horizontal stress direction. This is because, this orientation is the tangential stress has to overcome the smallest formation tensile strength.</td><td>
</td></tr>
</table>

Conclusion

The application of relatively new technologies (underbalanced drilling, slimhole completions, re-entry wells with open hole buildup sections, and multilateral wells) have to take into consideration, during the well planning stage, the risk of wellbore instability. The objective of a wellbore stability assessment is to quantify the influence of those parameters that affect the integrity of a given well such as lack of sufficient wellbore pressure, pore pressure transmission, hole inclination and others. The results of the wellbore stability assessment have to be used to mitigate the consequences of the instability. A wide variety of analytical and numerical models exist for prediction wellbore stresses and modes of instability for nearly all possible loading conditions, well geometries, rock properties and wellbore fluids. Dedicated laboratory tests and in-situ stress measurements are desirable to have more confidence in predictions achieved with analytical or numerical modeling tools. Every well should be evaluated individually based on next criteria: the type of anticipated problems, their potential severity, the quantity and quality of data needed for a proper analysis, time and budget, and the success of previous analyses of particular type.

Accepted:03.08.2007.

Received:05.09.2007.

Nomenclature:

a_z = Well azimuth, degree
C_o = Cohesive strength, Pa
E = Young´s modulus, Pa
i_w = Well Inclination, degrees
P_p = Pore pressure, Pa
P_i = Initial pore pressure, Pa
p_w = Wellbore pressure, Pa
r = Near wellbore position, m
r_w = Wellbore radius, m
T_i = Initial formation temperature, degrees
T_w = Wellbore wall temperature, degrees
θ = Point location angle, degrees

φ = Internal friction angle, degrees
σ_1 = Maximum principle stress, Pa
σ_2 = Medium principle stress, Pa
σ_3 = Minimum principle stress, Pa
σ_h = Minimum in-situ horizontal stress, Pa
σ_H = Maximum in-situ horizontal stress, Pa
T_o = The tensile strength of formation rock, Pa
σ_r = Radial normal stress at wellbore, Pa
σ_t = Hoop stress at wellbore, Pa
σ_a = Axial stress at wellbore, Pa
σ_x = Normal stress in x-direction, Pa
σ_y = Normal stress in y-direction, Pa
σ_x = Axial stress, Pa
$\tau_{\theta z}$ = Shear stress at wellbore, Pa
τ_{rz} = Shear stress at wellbore, Pa
$\tau_{r\theta}$ = Shear stress at wellbore, Pa
τ_{xy} = In-situ shear stress in (x,y,z) coordintaed system, Pa
τ_{yz} = In-situ shear stress in (x,y,z) coordintaed system, Pa
τ_{zz} = In-situ shear stress in (x,y,z) coordintaed system, Pa
ν = Poisson ration, dimensionless
α_p = Biot´s constant, dimensionless
α_t = Volumetric-thermal-expansion-constant, degrees^{-1}

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This paper is based on results of research on the project 195-1951390-1394 "Rocks/drilling Fluids Interaction Studies" financed by Ministry of Science, Education and Sports.