بسم الله الرحمن الرحيم

Sudan University of Science and Technology
College of Petroleum and Mining Engineering
Department of Exploration Engineering

Factors Influencing Wellbore Stability during Underbalanced Drilling

Prepared by:

- **HASSAN MOHAMED HASSAN KHALED**
- **MUTAMN ISHAQ ABDALLAH ABDALMAOLAH**
- **MOHAMMED ALFADIL RAHMTALLAH ALFADIL**
- **MOHAMMED ALMOSTAFA ISMAIL BASHER**

Supervisor:

Dr. ABD ALHAKAM ALTAYB MOHAMED

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الاستهلال

بسم الله الرحمن الرحيم

قال تعالى:

(فَتَعَالَى اللَّهُ الْمَلِكُ الْحَقُّ ۗ وَلَا تَعْجَلْ بِالْقُرْآنِ
مِنْ قَبْلِ أَنْ يُقْضَىٰ إِلَيْكَ وَحْيُهُ ۖ وَقُلْ رَبِّ
زِدْنِي عِلْمًا)

صدق الله العظيم
سورة طه الايه١١٤

Dedication

To our parents who stayed up for us

To our teachers who are dedicated to teaching us

To all loved ones and friends

Acknowledgment

It is our pleasure to extend our deep thanks and gratitude to **DR.Abdalhakm Eltayeb Mohamed** for his extended supports and directions to gain the most from this research Many thanks also to all College of Petroleum and mining Engineering (Exploration Department).

Abstract

Underbalanced drilling (UBD) of vertical wells has been one of the efficient technologies in the exploration and development of oil and gas fields, while wellbore instability poses a problem during the whole operation process, for fluid seepage induced by the flow of formation fluid into wellbore exerts additional stresses on wellbore. However, the impact of fluid seepage has usually been ignored by conventional analysis of wellbore stability during UBD. This paper, taking the effects from fluid seepage into consideration, introduces a new collapse pressure model for UBD of horizontal wells. A comparison of the new model with the conventional one reveals that maximum equivalent collapse density (MECD) reduces with the decrease of borehole radius and that the wellbore is more stable in a slim hole during UBD of horizontal wells. And with the change of the inclination angle, MECD is higher when fluid seepage is considered under a certain relative azimuthal angle, indicating a narrower mud weight window and a more unstable wellbore; while the variation trend of MECD with the inclination angle are quite different at relative azimuthal angle =90_ and 0_. With the change of the relative azimuthal angle, MECD obtained in consideration of fluid seepage is also greater when the inclination angles is fixed, and MECD in both conditions (when fluid seepage is considered and) decreases with the increase of the relative azimuthal angle; meanwhile, the value of q where MECD is obtained is also analyzed.

التجريد

يؤدي حفر الابار النفطية في ظل ظروف تسرب السوائل الناتج عن تدفق موائع التكوين إلى حفرة البئر إلى ضغوط إضافية على حفرة البئر. مع ذلك، عادة ما يتم تجاهل تأثير تسرب السوائل من خلال التحليل التقليدي لاستقرار حفرة البئر اثناء الحفر(UBD). يأخذ هذا المشروع في الاعتبار أثر تسرب السوائل من خلال استخدام نموذج ضغط الانهيار اثناء الحفر(UBD)للبئر الافقي يكشف استخدام هذا النموذج أن الحد الأقصى لكثافة الانهيار المكافئة (MECD) تقل مع نقصان نصف قطر البئر وأن البئر يكون أكثر استقرارا . وأيضا مع تغير زاوية الميل تكون أعلى عندما يتم النظر إلى تسرب السوائل عند زاوية سمتيه نسبيه معينه .

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Nomenclature& Abbreviations

σ_v : vertical stress

σ_H : maximum horizontal stress

σ_h : minimum horizontal stress

$(x' \square\, y' \square\, z')$: is the coordinate of in-situ stress

ox', oy', oz' : correspond to the directions of maximum horizontal stress ,minimum horizontal stress, and vertical stress.

$(x \square\, y \square\, z)$: is the coordinate of the wellbore.

Oz : corresponds to the axis of wellbore.

Ox , Oy: in the plane perpendicular to wellbore axis.

α : is relative horizontal stress to the projection line of well axis into the rectangular azimuthal angle which is the angle from the direction of maximum coordinate $(x' \square\, y' \square\, z')$.

$(\sigma_{xx}, \sigma_{yy}, \sigma_{zz}, \tau_{xy}, \tau_{yz}, \tau_{zx})$: relationship between rectangular coordinate $(x' \square\, y' \square\, z')$ and rectangular coordinate $(x \square y \square\, z)$.

P_{mud}: effective fluid column pressure.

R: is borehole radius.

r: is the radial distance from wellbore axis to some point in the formation.

θ: is the angle between the direction of radius vector and the direction of ox in the rectangular coordinate $(x \square\, y \square\, z)$.

υ: is Poisson's ratio.

σ_r: is a principal stress

σ_r^f : additional radial stress.

σ_θ^f : additional tangential stress.

σ_z^f : additional axial stress.

$\sigma_{\theta max}^f$, $\sigma_{\theta min}^f$,σ_r^f : maximum principal stress, intermediate principal stress and minimum principal stress.

P_{op} : is original pore pressure, MPa;

r_e: is the radius of external boundary, m.

σ_1^e and σ_3^e : are effective maximum principal stress and effective minimum principal stress, MPa

Φ : is the internal friction angle of rock.

C : is the cohesion strength of rock, MPa

$p_{cap:}$ capillary pressure

σ: is the interfacial tension

ϴ: is the contact angle between the two fluids
r: $is\ the\ pore - throat\ radius$
$a_{s:}$ activity in shale pore fluid
$a_{m:}$ activity in drilling mud
$P_{os\ :}$ osmotic pressure
$\mu_{c:}$ chemical potential
E_m: certain efficiency
$P_{wfl:}$ borehole $-$ fluid pressure

Abbreviations

UBD: Under balanced drilling
ECD: equivalent collapse density
MECD: maximum equivalent collapse density
FS: means the conditions with fluid seepage as a consideration
FSN: means the conditions with fluid seepage not as a consideration
WBF: water-based fluid
OBFs: oil-based fluids
SBFs: synthetic circulation density
BOP: blowout preventer
IADC: intl.ASSn Of Drilling Contractors
BHP: bottom hole pressure
PWD: pressure while drilling
OBD: Overbalanced drilling

Chapter One

Introduction

١.1 Introduction

Wellbore instability has remained one of common problems in the exploration of oil and gas, which amounts to huge expenses during oil and gas drilling. Therefore, maintaining a stable wellbore of great significance in the drilling and production of oil and gas wells. Since underbalanced drilling (UBD) is capable of improving rate of penetration and minimizing formation damage, horizontal wells is one of the technologies which can enhance well productivity, combination of these two technologies has been widely practiced, which has been proved to be highly efficient. During UBD of horizontal wells, effective fluid column pressure is lower than the formation pressure, this increases the chances of wellbore collapse, and influencing factors like well structure and well trajectory also affect wellbore stability.

Researches on wellbore stability have been conducted from various perspectives. For overbalanced drilling, types of formation rocks and drilling fluid have certain impact on wellbore stability. Chen et al. (2003) presented coupled numerical analyses to investigate the influence of fractures in the rock and Zhang et al. (2003) used dual-porosity poroelastic theory to solve the problem of horizontal well stability. Zeynali (2012) summed up types of wellbore instability from the mechanical and physico-chemical aspect during overbalanced drilling operations; and he concluded that properties of drilling mud and its interaction with the formation would affect the mechanical properties of the formation rocks and the stresses around the wellbore, especially for shale (van Oort, 2003). However, mechanical factors are the main factors that affect the stability of wellbore during UBD operations. When analyzing the effect of well structure and well trajectory on wellbore stability in overbalanced drilling, Zhang et al. (2010) and Manshad et al. (2014) used different rock strength criteria to assess wellbore stability of vertical, deviated and horizontal boreholes. And based on the results of wellbore stability analysis, Zare- Reisabadi et al. (2012) defined the optimal well trajectory during drilling and production in different in-situ stress regimes. Meanwhile, Kadyrov and Tutuncu (2012) incorporated borehole stability, lost circulation, hole cleaning and differential sticking for well trajectory optimization, after which recommendations for field development had been made to reduce non-productive time during drilling operations. Dutta and Farouk (2008) used a proper mechanical earth model from a nearby offset well to study wellbore failure based on well trajectory sensitivity analysis, which helped safe drilling of a horizontal well. However, there are a few studies about the influence of well trajectory and well structure on wellbore stability during UBD. To keep wellbore

stable during UBD operations, different models have been established. Salehi et al. (2007) used an elastoplastic model combined with a finite-explicit code to estimate optimum equivalent circulating density where UBD is applied. Mclellan and Hawkes (2001) developed a software called STABView ™to determine the optimal range of bottom hole pressure for UBD operations and to guide UBD operations in sandstone reservoirs. Moos et al. (2003) held that rocks had scale dependent strengths and he developed a model to predict regions where compressive shear failure would occur and anticipate spalling areas. Qiu et al. (2007) presented a practical wellbore stability technique to evaluate UBD in a horizontal well in depleted reservoir; and they conducted trajectory sensitivity analysis to design preferred borehole trajectories by which wellbore instability can be minimized, but in which effects of fluid seepage wasn't fully described. Meanwhile, thermal effect on rock failure in gas-drilling
was also studied (Li et al., 2014). However, models analyzing the influence of well structure and well trajectory on wellbore stability when considering fluid seepage in UBD haven't been fully studied.

This paper, by incorporating circumferential stresses produced by in-situ stress and additional stresses induced by fluid seepage, a new collapse pressure model for UBD of horizontal wells is introduced using MohreCoulomb criterion. Meanwhile, by comparing it with the conventional model in which fluid seepage is ignored, the impact of well structure and well trajectory (inclination angle and relative azimuthal angle) on wellbore stability during UBD of horizontal is put forward.

stresses produced by the flow of formation fluid into wellbore. It is assumed that UBD is liquid phase or gaseliquid underbalanced drilling, that formation rocks are fully saturated with formation fluid, and are isotropic, homogeneous, continuous and porous media, that formation fluid is single-phase and incompressible fluid and that fluid seepage is a steady flux without effects of time and temperature considered .

1.2 Objectives

-Study of the effect of relative azimuth angle on borehole stability.

-Study of the effect of the inclination angle on wellbore stability.

-Study of the effect of drilling trajectory on borehole stability.

-Study of the effect of well structure on borehole stability.

Chapter2

THE ORETICAL BACKGROUND & LITERATURE REVIEW

2.1 Stresses Around Wellbores

H.M. Westergaard published a paper entitled "Plastic State of Stress Arounda Deep Well" in 1940. This now-classic paper defined the wellbore stability problem as follows. The analysis that follows is a result of conversations with Dr. KarlTerzaghi who raised this question: What distributions of stress are possible inthe soil around an unlined drill hole for a deep well? What distributions of stress make it possible for the hole not to collapse but remain stable for sometime, either with no lining or with a thin "stove pipe" lining of small structural strength? Westergaard uses stress functions in cylindrical coordinates to solve the elastic-plastic wellbore problem for zero pressure in the hole and all normal stress components equal to the overburden far from the hole. Hooke's law was applied for the elastic region and a Coulomb yield condition* where "the limiting curve for Mohr's circle is a straight line" was assumed for the plastic region. His conclusions were: The plastic action makes it possible for the great circumferential pressures that are necessary for stability to occur not at the cylindrical surface of the hole but at some distance behind the surface, where they may be combined with sufficiently great radial pressures. The formulas that have been derived serveto explain the circumstances under which the drill hole for a deep well may remain stable. Westergaard's elasticity solution agrees with the Lame solution for a thick-walled cylinder subjected to the same boundary conditions. Hubbert and Willis (1957) demonstrated how earth stresses can vary from regions of normal faulting to those with thrust faulting. On the basis of a Coulomb failure model, they suggest that the maximum value of the ratio of the maximum to the minimum principal stress in the earth's crust should be about 3:1.

2.2 Borehole instability

Borehole instability is the undesirable condition of an openhole interval that does not maintain its gauge size and shape and/or its structural integrity. This articles discusses the causes, types, effects, and possible prevention of borehole instability.

2.1.1 Causes

The causes can be grouped into the following categories:

- Mechanical failure caused by in-situ stresses
- Erosion caused by fluid circulation
- Chemical caused by interaction of borehole fluid with the formation

2.1.2Types and associated problems:

There are four different types of borehole instabilities:

- Hole closure or narrowing
- Hole enlargement or washouts
- Fracturing
- Collapse

Fig. 1 illustrates hole-instability problems.

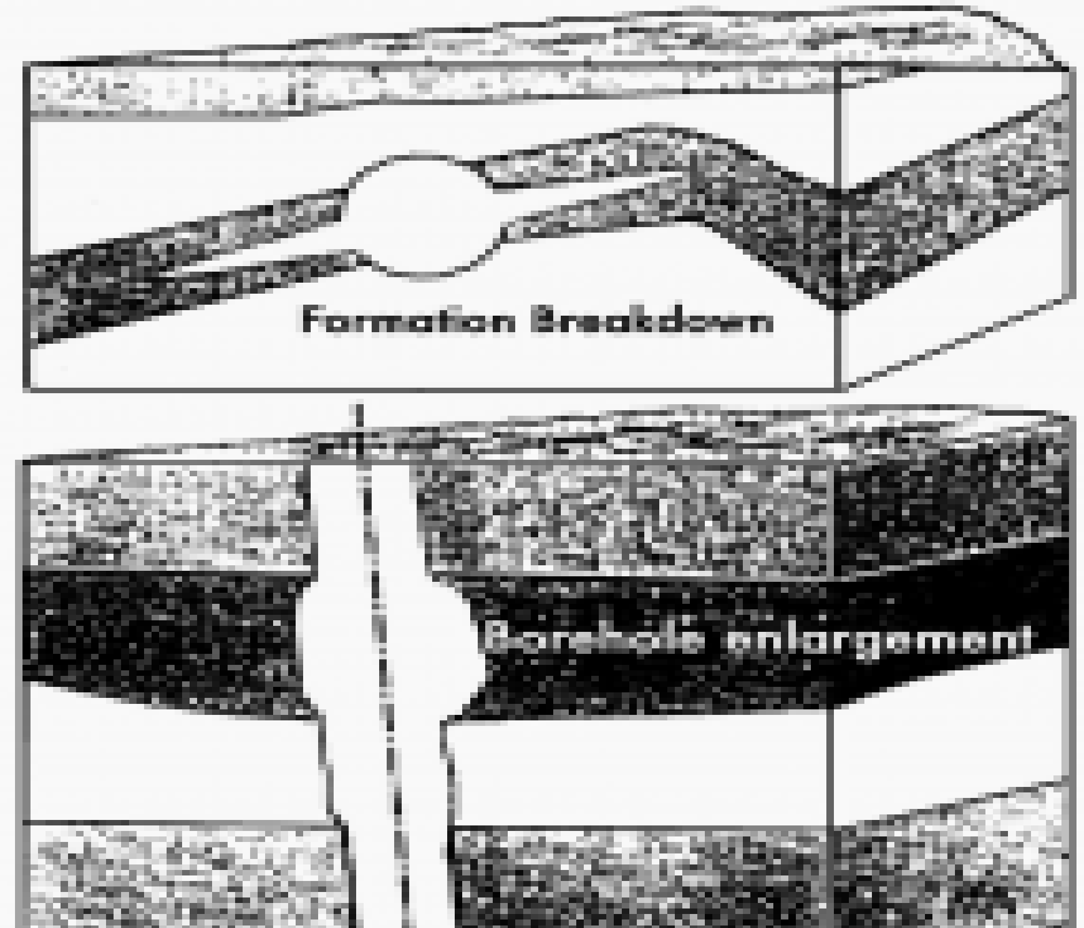
- 

Fig. 1—Types of hole instability problems.

2.1.2.1 Hole closure

Hole closure is a narrowing time-dependent process of borehole instability. It sometimes is referred to as creep under the overburden pressure, and it generally occurs in plastic-flowing shale and salt sections. Problems associated with hole closure are:

- Increase in torque and drag
- Increase in potential pipe sticking
- Increase in the difficulty of casings landing

2.1.2.2 Hole enlargement

Hole enlargements are commonly called washouts because the hole becomes undesirably larger than intended. Hole enlargements are generally caused by:

- Hydraulic erosion
- Mechanical abrasion caused by drill string
- Inherently sloughing shale

The problems associated with hole enlargement are:

- Increase in cementing difficulty
- Increase in potential hole deviation
- Increase in hydraulic requirements for effective hole cleaning
- Increase in potential problems during logging operations.

2.1.2.3 Fracturing

Fracturing occurs when the wellbore drilling-fluid pressure exceeds the formation-fracture pressure. The associated problems are lost circulation and possible kick occurrence.

2.1.2.4 Collapse

Borehole collapse occurs when the drilling-fluid pressure is too low to maintain the structural integrity of the drilled hole. The associated problems are pipe sticking and possible loss of well.

2.3 Principles of borehole instability

Before drilling, the rock strength at some depth is in equilibrium with the in-situ rock stresses (effective overburden stress, effective horizontal confining stresses). While a hole is being drilled, however, the balance between the rock strength and the in-situ stresses is disturbed. In addition, foreign fluids are introduced, and an interaction process begins between the formation and borehole fluids. The result is a potential hole-instability problem. Although a vast amount of research has resulted in many borehole-stability simulation models, all share the same shortcoming of uncertainty in the input data needed to run the analysis. Such data include:

- In-situ stresses
- Pore pressure
- Rock mechanical properties
- Formation and drilling-fluids chemistry

2.4 Mechanical rock-failure mechanisms

Mechanical borehole failure occurs when the stresses acting on the rock exceed the compressive or the tensile strength of the rock. Compressive failure is caused by shear stresses as a result of low mud weight, while tensile failure is caused by normal stresses as a result of excessive mud weight**.**

2.5 Shale instability

Shales make up the majority of drilled formations, and cause most wellbore-instability problems, ranging from washout to complete collapse of the hole. Shales are fine-grained sedimentary rocks composed of clay, silt, and, in some cases, fine sand. Shale types range from clay-rich gumbo (relatively weak) to shaly siltstone (highly cemented), and have in common the characteristics of extremely low permeability and a high proportion of clay minerals.

2.6 Mechanical instability

As stated previously, mechanical rock instability can occur because the in-situ stress state of equilibrium has been disturbed after drilling.

2.7 Chemical instability

Chemical-induced shale instability is caused by the drilling-fluid/shale interaction, which alters shale mechanical strength as well as the shale pore pressure in the vicinity of the borehole walls. The mechanisms that contribute to this problem include:

- Capillary pressure
- Osmotic pressure
- Pressure diffusion in the vicinity of the borehole walls
- Borehole-fluid invasion into the shale when drilling overbalanced

2.7.1 Capillary pressure

During drilling, the mud in the borehole contacts the native pore fluid in the shale through the pore-throat interface. This results in the development of capillary pressure, p_{cap} , which is expressed as

$$p_{\mathrm{cap}} = 2\sigma \cos\theta / r, \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

where σ is the interfacial tension, Θ is the contact angle between the two fluids, and r is the pore-throat radius.

2.7.2 Osmotic pressure

When the energy level or activity in shale pore fluid, a_s, is different from the activity in drilling mud. The mud activity can be reduced by adding electrolytes that can be brought about through the use of mud systems such as:

- Seawater
- Saturated-salt/polymer
- KCl/NaCl/polymer
- Lime/gypsum

2.7.3 Pressure diffusion

Pressure diffusion is a phenomenon of pressure change near the borehole walls that occurs over time. This pressure change is caused by the compression of the native pore fluid by the borehole-fluid pressure, p_{wfl}, and the osmotic pressure, p_{os}.

2.8 Use of drilling fluid

Drilling overbalanced through a shale formation with a water-based fluid (WBF) allows drilling-fluid pressure to penetrate the formation. Because of the saturation and low permeability of the formation, the penetration of a small volume of mud filtrate into the formation causes a considerable increase in pore-fluid pressure near the wellbore wall. The increase in pore-fluid pressure reduces the effective mud support, which can cause instability.

2.9 Borehole-instability prevention

Total prevention of borehole instability is unrealistic, because restoring the physical and chemical in-situ conditions of the rock is impossible. However, the drilling engineer can mitigate the problems of borehole instabilities by adhering to good field practices. These practices include:

- Proper mud-weight selection and maintenance
- Use of proper hydraulics to control the equivalent circulating density (ECD)
- Proper hole-trajectory selection
- Use of borehole fluid compatible with the formation being drilled

Additional field practices that should be followed are:

- Minimizing time spent in open hole
- Using offset-well data (use of the learning curve)
- Monitoring trend changes (torque, circulating pressure, drag, fill-in during tripping)
- Collaborating and sharing information**.**

2.10 Underbalanced drilling (UBD)

In underbalanced drilling (UBD), the hydrostatic head of the drilling fluid is intentionally designed to be lower than the pressure of the formations that are being drilled. The hydrostatic head of the fluid may naturally be less than the formation pressure, or it can be induced by adding different substances to the liquid phase of the drilling fluid, such as:

- Natural gas
- Nitrogen
- Air

Whether the underbalanced status is induced or natural, the result may be an influx of formation fluids that must be circulated from the well, and controlled at surface.

2.10.1 Characteristics of UBD

The effective downhole circulating pressure of the drilling fluid is equal to the hydrostatic pressure of the fluid column, plus associated friction pressures, plus any pressure applied on surface.

$$\text{Overbalanced Drilling (OBD)}: P_{\text{reservoir}} < P_{\text{bottom hole}} = P_{\text{hydrostatic}} + P_{\text{friction}} + P_{\text{choke}}.$$

$$\text{UBD}: P_{\text{reservoir}} > P_{\text{bottom hole}} = P_{\text{hydrostatic}} + P_{\text{friction}} + P_{\text{choke}}.$$

Conventionally, wells are drilled overbalanced. In these wells, a column of fluid of a certain density in the hole provides the primary well-control mechanism. The pressure on the bottom of the well will always be designed to be higher than the pressure in the formation (Fig. 1a). In underbalanced drilled wells, a lighter fluid replaces the fluid column, and the pressure on the bottom of the well is designed intentionally to be lower than the pressure in the formation (Fig. 1b).

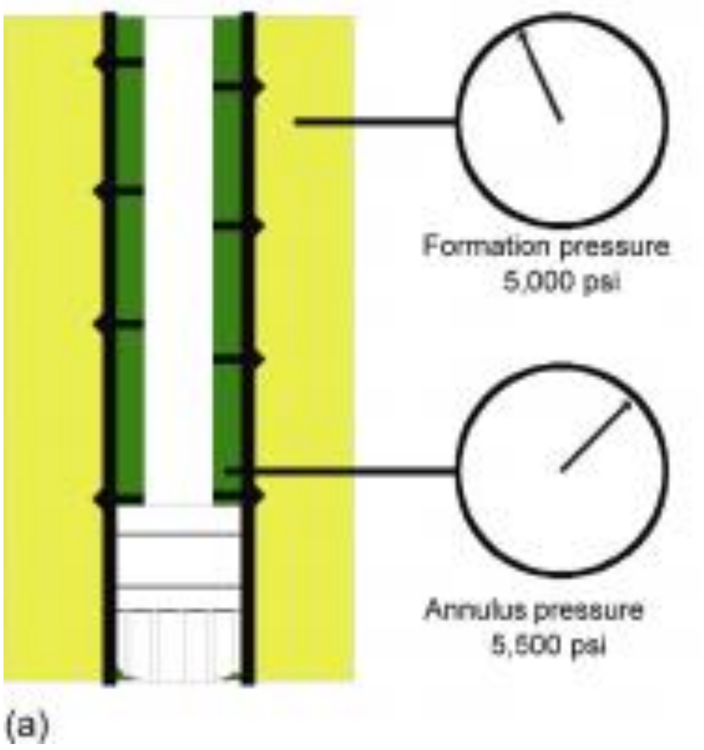


Fig. 2.10.1—Pressures in conventional drilling.

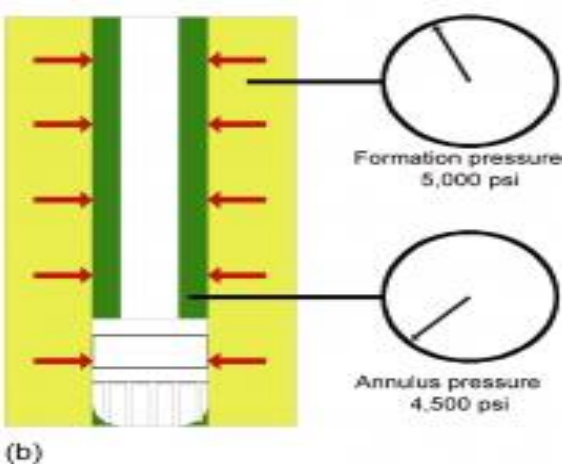


Fig. 2.10.2—Pressures in underbalanced drilling.

Because the fluid no longer acts as the primary well-control mechanism, the primary well control in UBD arises from three different mechanisms:

- Hydrostatic pressure (passive) of materials in the wellbore because of the density of the fluid used (mud) and the density contribution of any drilled cuttings.

- Friction pressure (dynamic) from fluid movement because of circulating friction of the fluid used.

- Choke pressure (confining or active), which arises because of the pipe being sealed at surface, resulting in a positive pressure at surface.

Flow from any porous and permeable zones is likely to result when drilling underbalanced. This inflow of formation fluids must be controlled, and any hydrocarbon fluids must be handled safely at surface. The lower hydrostatic head avoids the buildup of filter cake on the formation as well as the invasion of mud and drilling solids into the formation. This helps to improve productivity of the well and reduce related drilling problems. UBD produces an influx of formation fluids that must be controlled to avoid well-control problems. This is one of the main differences from conventional drilling. In conventional drilling, pressure control is the main well control principle, while in UBD, flow control is the main well-control principle. In UBD, the fluids from the well are returned to a closed system at surface to control the well. With the well flowing, the blowout preventer (BOP) system is kept closed while drilling, whereas, in conventional overbalanced operations, drilling fluids are returned to an open system with the BOPs open to atmosphere (Fig. 2). Secondary well control is still provided by the BOPs, as is the case with conventional drilling operations.

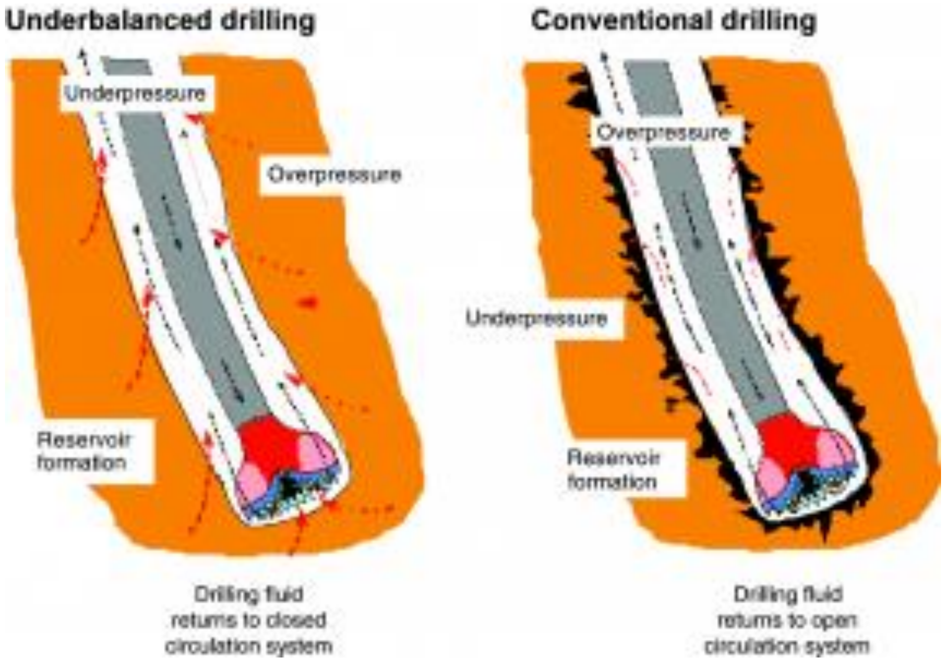


Fig. 2.10.3—Open vs. closed circulation systems.

2.10.2 Lowhead drilling

Lowhead drilling is drilling with the hydrostatic head of the drilling fluid reduced to a pressure marginally higher than the pressure of the formations being drilled. The hydrostatic head of the fluid is maintained above the formation pressure, and reservoir inflow is avoided. Lowhead drilling may be undertaken in formations that would produce H_2S, or would cause other issues, if hydrocarbons were produced to surface.

2.10.3 Reasons to consider underbalanced drilling

The reasons for UBD can be broken down into two main categories:

- Maximizing hydrocarbon recovery.
- Minimizing pressure-related drilling problems.

There are also specific advantages and disadvantages of performing a drilling operation underbalanced. These are summarized in Table 1.

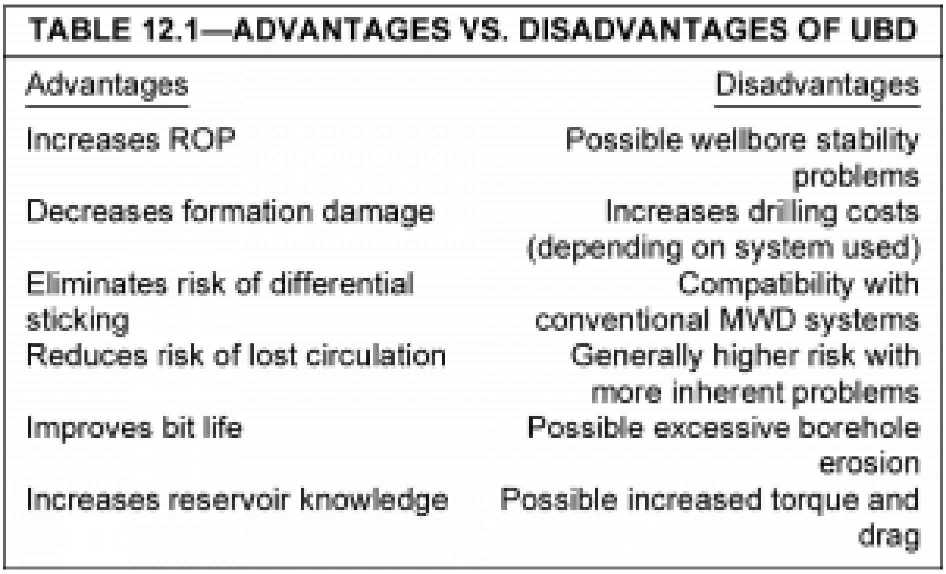
- 

TABLE 12.1—ADVANTAGES VS. DISADVANTAGES OF UBD

Advantages	Disadvantages
Increases ROP	Possible wellbore stability problems
Decreases formation damage	Increases drilling costs (depending on system used)
Eliminates risk of differential sticking	Compatibility with conventional MWD systems
Reduces risk of lost circulation	Generally higher risk with more inherent problems
Improves bit life	Possible excessive borehole erosion
Increases reservoir knowledge	Possible increased torque and drag

Table 2.1-Advantages vs. disadvantages of UBD

2.10.4 Early production

The well is producing as soon as the reservoir is penetrated with a bit.

2.10.5 Reduced stimulation

Because there is no filtrate or solids invasion in an underbalanced drilled reservoir, the need for reservoir stimulation, such as acid washing or massive hydraulic fracture stimulation, is eliminated.

2.10.6 Enhanced recovery

Because of the increased productivity of an underbalanced drilled well combined with the ability to drill infill wells in depleted fields, the recovery of bypassed hydrocarbons is possible. This can significantly extend the life of a field. The improved productivity of the wells also leads to a lower drawdown, which, in turn, can reduce water coning.

2.10.7 Increased reservoir knowledge

During an underbalanced drilling operation, reservoir productivity and the produced fluids can be measured and analyzed while drilling. This allows a well to be drilled longer or shorter, depending on production requirements.

2.10.8 Minimizing pressure-related drilling problems

2.10.8.1 Differential sticking

The absence of an overburden on the formation combined with the lack of any filter cake serves to prevent the drill string from becoming differentially stuck. This is especially useful when drilling with coiled tubing, because coiled tubing lacks tool joint connections that increase the standoff in the borehole and then helps minimize sticking of conventional drill pipe.

2.10.8.2 No losses

In general, a reduction of the hydrostatic pressure in the annulus reduces the fluid losses into a reservoir formation. In UBD, the hydrostatic pressure is reduced to a level at which losses do not occur. This is especially important in the protection of fractures in a reservoir.

2.10.8.3 Improved penetration rate

The lowering of the wellbore pressure relative to the formation pressure has a significant effect on penetration rate. The reduction in the “chip hold down effect” also has a positive impact on bit life. The increased penetration rate combined with the effective cuttings removal from the face of the bit leads to a significant increase in bit life. In underbalanced drilled wells, sections have been drilled with only one bit where an overbalanced drilled well might need anywhere from three to five bits. It is normally assumed that penetration rates double when drilling underbalanced.

2.10.9 Classification system for underbalanced drilling

A classification system developed by the Intl. Assn. of Drilling Contractors (IADC) is helping establish the risks associated with underbalanced drilled wells (Table 2).

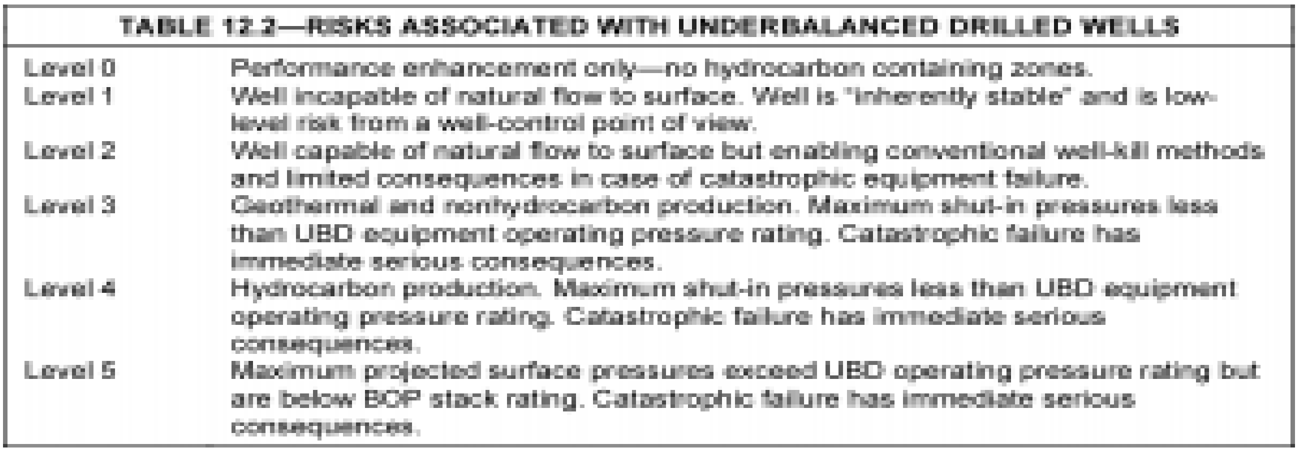
- 

TABLE 12.2—RISKS ASSOCIATED WITH UNDERBALANCED DRILLED WELLS

Level 0	Performance enhancement only—no hydrocarbon containing zones.
Level 1	Well incapable of natural flow to surface. Well is "inherently stable" and is low-level risk from a well-control point of view.
Level 2	Well capable of natural flow to surface but enabling conventional well-kill methods and limited consequences in case of catastrophic equipment failure.
Level 3	Geothermal and nonhydrocarbon production. Maximum shut-in pressures less than UBD equipment operating pressure rating. Catastrophic failure has immediate serious consequences.
Level 4	Hydrocarbon production. Maximum shut-in pressures less than UBD equipment operating pressure rating. Catastrophic failure has immediate serious consequences.
Level 5	Maximum projected surface pressures exceed UBD operating pressure rating but are below BOP stack rating. Catastrophic failure has immediate serious consequences.

Table2. 2-Risks Associated With UBD Wells

The matrix given easily classifies the majority of known underbalanced applications. This system combines the risk management categories (Levels 0 to 5) with a subclassifier to indicate either “underbalanced” or “low head” drilling using underbalanced technology. To provide a complete method of classifying the type of technology used for one or more sections of a well, or multiple wells in a particular project, a third component of the classification system addresses the underbalanced technique used, as shown in Table 3.

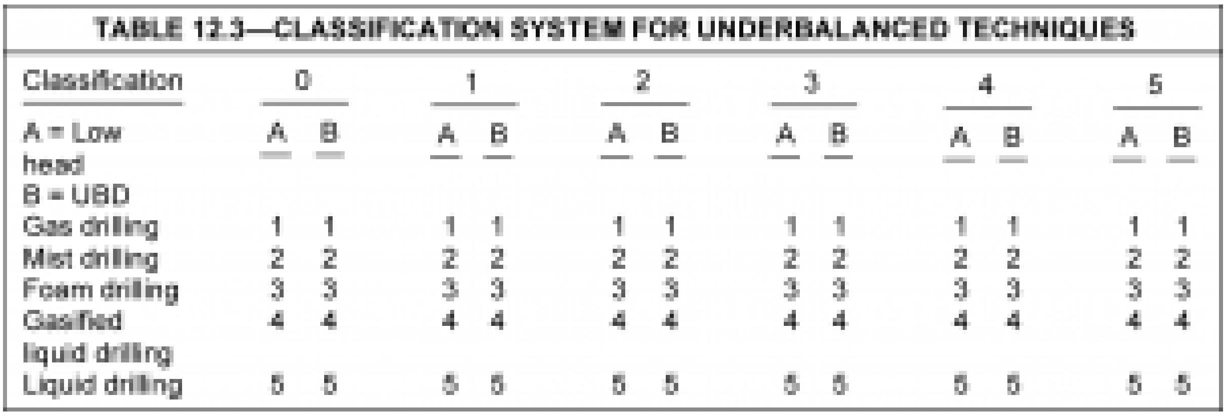
- 

TABLE 12.3—CLASSIFICATION SYSTEM FOR UNDERBALANCED TECHNIQUES

Classification	0		1		2		3		4		5	
A = Low head B = UBD	A	B	A	B	A	B	A	B	A	B	A	B
Gas drilling	1	1	1	1	1	1	1	1	1	1	1	1
Mist drilling	2	2	2	2	2	2	2	2	2	2	2	2
Foam drilling	3	3	3	3	3	3	3	3	3	3	3	3
Gasified liquid drilling	4	4	4	4	4	4	4	4	4	4	4	4
Liquid drilling	5	5	5	5	5	5	5	5	5	5	5	5

Table 2.3-Classification System for UBD Techniques

2.10.10 Selecting the right candidate for UBD

Most reservoirs can be drilled underbalanced, but some cannot, because of geological issues associated with rock stability. For some reservoirs, it might not be possible to drill underbalanced with the current technology, because they are either prolific producers, or pressures are so high that safety and environmental concerns prevent safe underbalanced drilling. These may include high-pressure or sour wells (although both types have been drilled underbalanced, but with significant engineering considerations and planning).

Candidate selection for UBD must focus not only on the benefits of UBD, but also on additional considerations. It is important that the right reservoir is selected for a UBD operation. Table 4 shows reservoir types that will and will not benefit from UBD. Of course, not only the reservoir has to be evaluated, but also the well design, the possible damage mechanisms, and the economic reasons for UBD. All issues must be considered carefully when choosing whether or not to drill underbalanced.

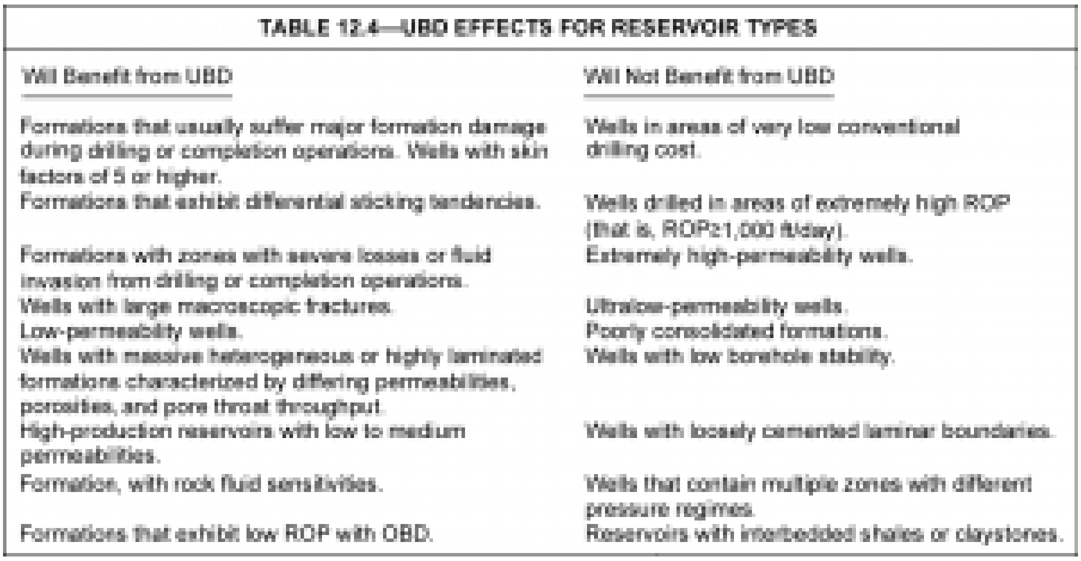
- 

TABLE 12.4—UBD EFFECTS FOR RESERVOIR TYPES

Will Benefit from UBD	Will Not Benefit from UBD
Formations that usually suffer major formation damage during drilling or completion operations. Wells with skin factors of 5 or higher.	Wells in areas of very low conventional drilling cost.
Formations that exhibit differential sticking tendencies.	Wells drilled in areas of extremely high ROP (that is, ROP≥1,000 ft/day).
Formations with zones with severe losses or fluid invasion from drilling or completion operations.	Extremely high-permeability wells.
Wells with large macroscopic fractures.	Ultralow-permeability wells.
Low-permeability wells.	Poorly consolidated formations.
Wells with massive heterogeneous or highly laminated formations characterized by differing permeabilities, porosities, and pore throat throughput.	Wells with low borehole stability.
High-production reservoirs with low to medium permeabilities.	Wells with loosely cemented laminar boundaries.
Formation, with rock fluid sensitivities.	Wells that contain multiple zones with different pressure regimes.
Formations that exhibit low ROP with OBD.	Reservoirs with interbedded shales or claystones.

Table 2.4-UBD Effects For Reservoir Types

2.10.11 Reservoir selection issues

Appropriate reservoir screening is essential for the correct selection of a suitable reservoir application for vertical or horizontal UBD. A systematic approach, outlined in the following section, identifies the major areas of study to ascertain if sufficient information is available to initiate the design work for a viable UBD process.

Once this information is gathered and reviewed, and if data show that an UBD operation is the best method for recovering hydrocarbons in an economically and technically successful manner, it is time to mobilize the team to design and execute the UBD operation. Steps in a typical UBD evaluation process are outlined in Table 5. Fig. 3 shows this UBD evaluation process as a flow chart.

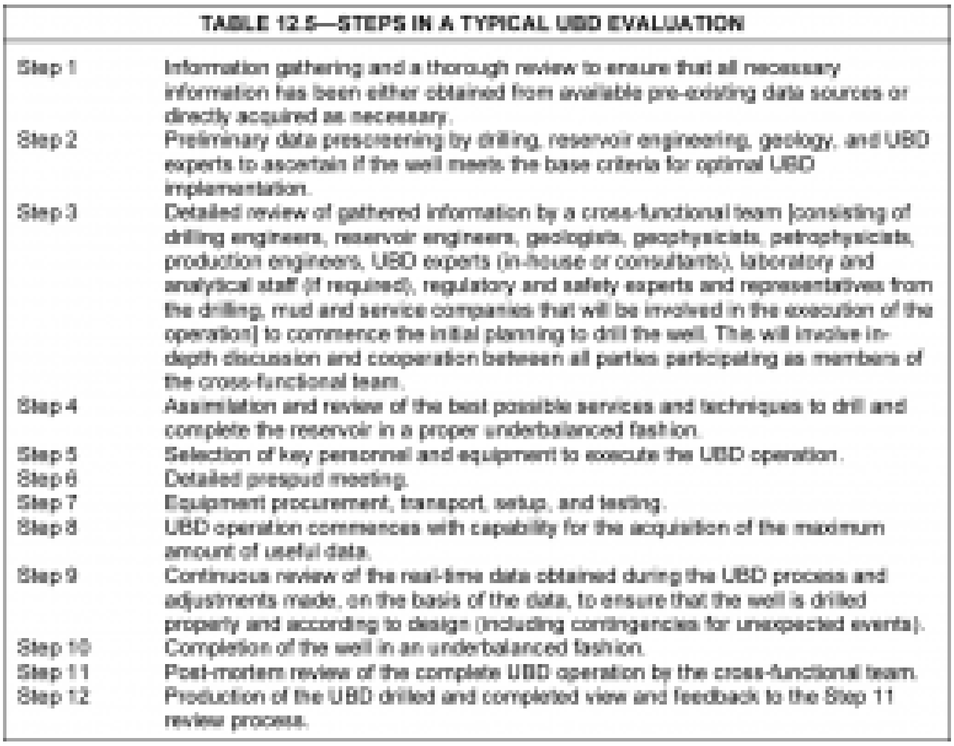
- 

TABLE 12.5—STEPS IN A TYPICAL UBD EVALUATION	
Step 1	Information gathering and a thorough review to ensure that all necessary information has been either obtained from available pre-existing data sources or directly acquired as necessary.
Step 2	Preliminary data prescreening by drilling, reservoir engineering, geology, and UBD experts to ascertain if the well meets the base criteria for optimal UBD implementation.
Step 3	Detailed review of gathered information by a cross-functional team [consisting of drilling engineers, reservoir engineers, geologists, geophysicists, petrophysicists, production engineers, UBD experts (in-house or consultants), laboratory and analytical staff (if required), regulatory and safety experts and representatives from the drilling, mud and service companies that will be involved in the execution of the operation] to commence the initial planning to drill the well. This will involve in-depth discussion and cooperation between all parties participating as members of the cross-functional team.
Step 4	Assimilation and review of the best possible services and techniques to drill and complete the reservoir in a proper underbalanced fashion.
Step 5	Selection of key personnel and equipment to execute the UBD operation.
Step 6	Detailed prespud meeting.
Step 7	Equipment procurement, transport, setup, and testing.
Step 8	UBD operation commences with capability for the acquisition of the maximum amount of useful data.
Step 9	Continuous review of the real-time data obtained during the UBD process and adjustments made, on the basis of the data, to ensure that the well is drilled properly and according to design (including contingencies for unexpected events).
Step 10	Completion of the well in an underbalanced fashion.
Step 11	Post-mortem review of the complete UBD operation by the cross-functional team.
Step 12	Production of the UBD drilled and completed view and feedback to the Step 11 review process.

Table2. 5-Steps in a Typical UBD Evaluation

2.10.12 Economic limitations

It is important not to forget the business driver behind the technology. If benefits cannot be achieved, the project must be reviewed. The improvements from UBD—increased penetration rate, increased production rate, and minimization of impairment—must offset the additional cost of undertaking a UBD project. This is often the most difficult limitation of UBD to overcome. If the reservoir/production engineers are not convinced that there is a sound reason for drilling underbalanced for productivity reasons, most underbalanced projects will never get past the feasibility stage. To drill a well underbalanced, extra equipment and people are required, and this adds to the drilling cost of a well. The operators must show a return for their shareholders, so they will want to know if this extra investment is worthwhile before embarking on a UBD project.

2.10.13 Costs associated with underbalanced drilling

The following factors contribute to the cost increases for an underbalanced drilled well in comparison to a conventionally drilled well:

- Pre-engineering studies.

- Rotating diverter system.
- Surface separation and well-control package.
- Snubbing system to deal with pipe light.
- Data acquisition system.
- Extra downhole equipment [nonreturn valves and pressure while drilling (PWD)].
- Special drill string connections (high-torque gas that is tight with special hardbanding).
- Additional personnel training.
- Additional operational wellsite personnel.
- Additional safety case update consistent with planned UBD operations.
- Extra time required to drill underbalanced.

From industry experience to date, we can state that underbalanced drilled wells are 20 to 30% more expensive than overbalanced drilled wells. This applies to both offshore and onshore operations in a similar area.

2.10.14 Reservoir studies

Prior to a UBD operation, some reservoir engineering work should be carried out. Not only is an accurate reservoir pressure needed, but the damage mechanism of the reservoir must be understood to ensure that the benefits of UBD can be obtained. Some wells or reservoirs are suitable for underbalanced operations, and result in an enhanced recovery. Other formations or fields may not be viable for a variety of reasons. If formation damage is the main driver for UBD, it is important that the reservoir and petroleum engineers understand the damage mechanisms resulting from overbalanced drilling (OBD). We must remember that even underbalanced drilled wells can cause formation damage.

Coreflush testing may be required to establish compatibility between the proposed drilling fluid and the produced reservoir fluids. This is critical if oil reservoirs are to be drilled underbalanced. The potential for scale and emulsion forming must also be reviewed prior to starting operations. We must ascertain the stability of the zone of interest to determine if the proposed well path is structurally capable of being drilled with the anticipated formation drawdown.

Expected productivity with the proposed drawdown must be reviewed. The objective of UBD is to clean the reservoir, and not to produce the well to its maximum capacity. If the reservoir is likely to produce any water, we must take this into account because water influx can have significant effects on the underbalanced process. It is important that expected productivity be analyzed with the reservoir engineers to obtain an accurate indicator as to whether UBD would be beneficial.

Once reservoir issues are fully understood, advantages to drilling underbalanced are proven, and the proposed well profile can be achieved, we can undertake the selection of the surface equipment.

Chapter Three

Methodology

3.1Circumferential stresses produced by in-situ stresses

In the whole drilling operation, three kinds of in-situ stresses act on the wellbore, namely, vertical stress (Ϭv), maximum horizontal stress (ϬH) and minimum horizontal stress (Ϭh). And during the drilling process of a horizontal well, as the angle of the well changes from vertical to deviated and to horizontal finally, stress state also changes. So before analyzing the circumferential stresses produced by in-situ stresses, coordinate systems of the wellbore should be set up. As Fig. 1(a) shows, rectangular coordinate (x0, y0, z0) is the coordinate of in-situ stress, while ox0, oy0, oz0 correspond to the directions of maximum horizontal stress (ϬH), minimum horizontal stress (Ϭh) and vertical stress (Ϭv) respectively; and rectangular coordinate (x, y, z) is the coordinate of the wellbore, where oz corresponds to the axis of wellbore, and ox and oy are in the plane perpendicular to wellbore axis. A study of the relationship between rectangular coordinate (x0 , y0, z0) and rectangular coordinate (x, y, z) yields six stress components (Ϭxx, Ϭyy, Ϭzz, txy, tyz, tyz) in the coordinate of wellbore (x, y, z) as Eq. (1) illustrates, where i is inclination angle, _; a is relative azimuthal angle which is the angle from the direction of maximum horizontal stress to the projection line of well axis into the rectangular coordinate (x0, y0, z0), _ (Fjaer et al., 2008).

$$\begin{cases} \sigma_{xx} = \sigma_H \cos^2 i \cos^2 \alpha + \sigma_h \cos^2 i \sin^2 \alpha + \sigma_v \sin^2 i \\ \sigma_{yy} = \sigma_H \sin^2 \alpha + \sigma_h \cos^2 \alpha \\ \sigma_{zz} = \sigma_H \sin^2 i \cos^2 \alpha + \sigma_h \sin^2 i \sin^2 \alpha + \sigma_v \cos^2 i \\ \tau_{xy} = -\sigma_H \cos i \cos \alpha \sin \alpha + \sigma_h \cos i \cos \alpha \sin \alpha \\ \tau_{yz} = -\sigma_H \sin i \cos \alpha \sin \alpha + \sigma_h \sin i \cos \alpha \sin \alpha \\ \tau_{zx} = \sigma_H \cos i \sin i \cos^2 \alpha + \sigma_h \cos i \sin i \sin^2 \alpha - \sigma_v \cos i \sin i \end{cases} \tag{1}$$

under the action of in-situ stresses (Ϭv, ϬH, Ϭh) and effective fluid column pressure Pmud in the borehole, the redistribution of circumferential stresses in Eq. (1) can be obtained by analyzing the function of six stress components (Ϭxx, Ϭyy, Ϭzz, txy, tyz,

tyz) on wellbore. A linear superposition of the six components gives the equation of circumferential stresses of deviated wellbore produced by in-situ stresses, which are expressed in Eq. (2).

$$\begin{cases} \sigma_r = P_{mud}\frac{R^2}{r^2} + \frac{\sigma_{xx}+\sigma_{yy}}{2}\left(1-\frac{R^2}{r^2}\right) + \frac{\sigma_{xx}-\sigma_{yy}}{2}\left(1-4\frac{R^2}{r^2}+3\frac{R^4}{r^4}\right)\cos 2\theta + \tau_{xy}\left(1-4\frac{R^2}{r^2}+3\frac{R^4}{r^4}\right) sin2\theta \\ \sigma_\theta = -P_{mud}\frac{R^2}{r^2} + \frac{\sigma_{xx}+\sigma_{yy}}{2}\left(1+\frac{R^2}{r^2}\right) - \frac{\sigma_{xx}-\sigma_{yy}}{2}\left(1+3\frac{R^4}{r^4}\right)\cos 2\theta - \tau_{xy}\left(1+3\frac{R^4}{r^4}\right) sin2\theta \\ \sigma_z = \sigma_{zz} - \nu\left[2(\sigma_{xx}-\sigma_{yy})\frac{R^2}{r^2}\cos 2\theta + 4\tau_{xy}\frac{R^2}{r^2}\sin 2\theta\right] \\ \tau_{r\theta} = \frac{\sigma_{yy}-\sigma_{xx}}{2}\left(1+2\frac{R^2}{r^2}-3\frac{R^4}{r^4}\right)\sin 2\theta + \tau_{xy}\left(1+2\frac{R^2}{r^2}-3\frac{R^4}{r^4}\right) cos2\theta \\ \tau_{\theta z} = \tau_{yz}\left(1+\frac{R^2}{r^2}\right)\cos\theta - \tau_{xz}\left(1+\frac{R^2}{r^2}\right)\sin\theta \\ \tau_{zr} = \tau_{xz}\left(1-\frac{R^2}{r^2}\right)\cos\theta + \tau_{yz}\left(1-\frac{R^2}{r^2}\right)\sin\theta \end{cases}$$

(2) where R is borehole radius, m; r is the radial distance from wellbore axis to some point in the formation, m; q is the angle between the direction of radius vector and the direction of ox in the rectangular coordinate (x, y, z), _; n is Poisson's ratio. And it can be seen that six stress solutions in Eq. (2) are related to q. In other words,circumferential stresses of deviated wellbore in cylindrical coordinate (r, q, z) vary with the change of spatial position of wellbore. Meanwhile, as shear stresses (trq, tqz, tqz) of the deviated wellbore rocks are usually not 0, Ϭr, Ϭq and Ϭz usually aren't the principal stresses of rock infinitesimal.

3.1.1Analysis of principal stresses of deviated wellbore

Stresses and collapse pressure at the wellbore wall are major considerations during the analysis of wellbore collapse of UBD in horizontal wells. So before the principal stresses of deviated wellbore are discussed, stress components of the deviated wellbore at wellbore wall (r = R) should be dealt with in Eq. (3).

$$\begin{cases} \sigma_r = P_{mud} \\ \sigma_\theta = -P_{mud} + (\sigma_{xx} + \sigma_{yy}) - 2(\sigma_{xx} - \sigma_{yy})\cos 2\,\theta - 4\tau_{xy} sin2\theta \\ \sigma_z = \sigma_{zz} - \nu\left[2(\sigma_{xx} - \sigma_{yy})\cos 2\,\theta + 4\tau_{xy}\sin 2\,\theta\right] \\ \tau_{\theta z} = 2\tau_{yz}\cos\theta - 2\tau_{xz}\sin\theta \\ \tau_{zr} = \tau_{r\theta} = 0 \end{cases} \tag{3}$$

From the circumferential stresses of deviated wellbore produced by in-situ stresses, it can be seen that stress component Ϭq and Ϭz in Eq. (3) are not the principal stresses, either. However, an analysis of the stress condition of the rock infinitesimal in Fig. 2(a) indicates that Ϭr is a principal stress, then wellbore plane of the deviated well is still a plane of principal stress. In order to get the positions where rocks of deviated wellbore break, another two planes of principal stress should be determined. Fig. 2(b) illustrates the state of biaxial stress at the deviated wellbore wall. There are two planes of principal stress (plane 1 and plane 2) which are perpendicular to each other, and the angle between plane 1 and oz (the direction of Ϭz) is b. Thereby, principal stress Ϭ, shear stress t and b can be expressed as Eqs. (4) and (5) by using the stress components in Eq. (3).

$$\begin{cases} \sigma = \sigma_\theta\cos^2\beta + 2\tau_{\theta z}\cos\beta\sin\beta + \sigma_z\sin^2\beta \\ \tau = 0.5(\sigma_z - \sigma_\theta)\sin 2\,\beta + \tau_{\theta z}\cos 2\,\beta \end{cases}$$

(4)

$$\tan 2\,\beta = -\frac{2\tau_{\theta z}}{\sigma_z - \sigma_\theta}$$

(5)

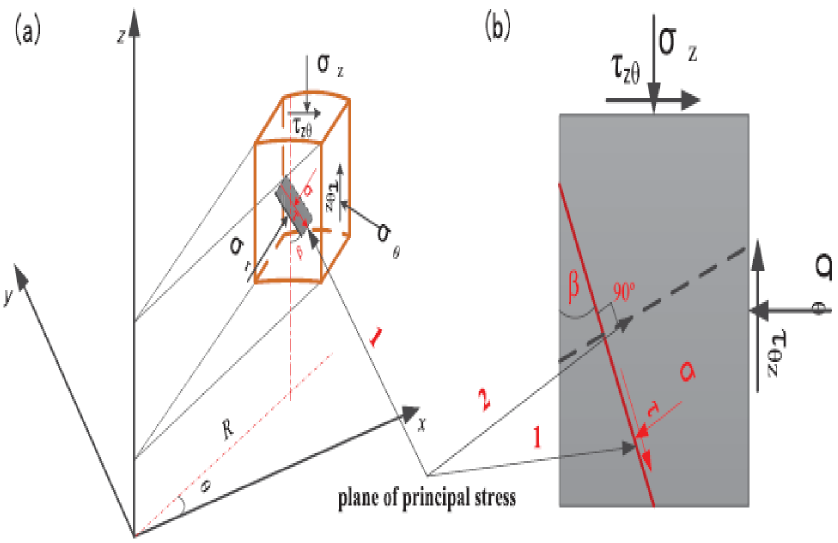


Fig. 2. (a) The stress condition of the rock infinitesimal in the cylindrical coordinate; (b) the stress condition of the rock infinitesimal plane where principal stresses are located.

Analysis of principal stresses of deviated wellbore Stresses and collapse pressure at the wellbore wall are major considerations during the analysis of wellbore collapse of UBD in horizontal wells. So before the principal stresses of deviated wellbore are discussed, stress components of the deviated wellbore at wellbore wall (r = R) should be dealt with in Eq. (3).

When dϬ/db =0, two principal stresses (Ϭ$_{0max}$ and Ϭ$_{0min}$) on plane 1 and plane 2 can be obtained. Based on those two principal stresses, we solve three principal stresses acting on the deviated wellbore under the principle of effective stress by Eq. (6), where ae is Biot's coefficient, and Pp is pore pressure, MPa.

$$\begin{cases} \sigma_r = P_{mud} - \alpha_e P_p \\ \sigma_{\theta \mathrm{max}} = 0.5(\sigma_\theta + \sigma_z) + 0.5\sqrt{(\sigma_\theta - \sigma_z)^2 + 4\tau_{\theta z}^2} - \alpha_e P_p \\ \sigma_{\theta \mathrm{min}} = 0.5(\sigma_\theta + \sigma_z) - 0.5\sqrt{(\sigma_\theta - \sigma_z)^2 + 4\tau_{\theta z}^2} - \alpha_e P_p \end{cases} \tag{6}$$

3.1.2Circumferential stresses produced by fluid seepage

Compared with conventional overbalanced drilling, effective fluid column pressure in the wellbore during UBD is lower than the formation pore pressure. To put it another way, formation fluid continuously flows into the wellbore during the operation of UBD and seepage stresses (Shin et al., 2010) are exerted on wellbore. Based on poromechanics and elastic mechanics and given assumptions, He et al. (2014) established analytical models to obtain circumferential stresses produced by fluid seepage, i.e. additional radial stress Ϭfr , additional tangential stress Ϭfq and additional axial stress Ϭfz :

$$\begin{cases} \sigma_r^f = \dfrac{r_e^2\left(r^2 - R^2\right)\left[2(1-\nu)(P_{op} - P_{mud}) + P_{op} - P_{mud}\right]}{2r^2\left(r_e^2 - R^2\right)(1-\nu)} - \dfrac{(P_{op} - P_{mud})\ln(r/R)}{2(1-\nu)\ln(r_e/R)} \\ \sigma_\theta^f = \dfrac{r_e^2\left(r^2 + R^2\right)\left[2(1-\nu)(P_{op} - P_{mud}) + P_{op} - P_{mud}\right]}{2r^2\left(r_e^2 - R^2\right)(1-\nu)} - \dfrac{(P_{op} - P_{mud})\left[\ln(r/R) + 2\nu - 1\right]}{2(1-\nu)\ln(r_e/R)} \\ \sigma_z^f = \dfrac{r_e^2\nu\left[2(1-\nu)(P_{op} - P_{mud}) + P_{op} - P_{mud}\right]}{(1-\nu)(r_e^2 - R^2)} - \dfrac{\nu(P_{op} - P_{mud})\left[2\ln(r/R) + 2\nu - 1\right]}{2(1-\nu)\ln(r_e/R)} \end{cases} \tag{7}$$

When r =R (at the wellbore wall), the stress components produced by fluid seepage can be expressed by Eq. (8), where Pop is original pore pressure, MPa; re is the radius of external boundary, m.

$$\begin{cases} \sigma_r^f = 0 \\ \sigma_\theta^f = \dfrac{r_e^2\left[2(1-\nu)(P_{op} - P_{mud}) + P_{op} - P_{mud}\right]}{(r_e^2 - R^2)(1-\nu)} - \dfrac{(P_{op} - P_{mud})\left[2\nu - 1\right]}{2(1-\nu)\ln(r_e/R)} \\ \sigma_z^f = \dfrac{r_e^2\nu\left[2(1-\nu)(P_{op} - P_{mud}) + P_{op} - P_{mud}\right]}{(1-\nu)(r_e^2 - R^2)} - \dfrac{\nu(P_{op} - P_{mud})\left[2\nu - 1\right]}{2(1-\nu)\ln(r_e/R)} \end{cases} \tag{8}$$

Based on the three principal stresses and circumferential stresses produced by fluid seepage, and considering pore pressure Pp =ϬPmud at the wellbore wall, circumferential stresses of UBD of horizontal wells at the wellbore wall are established, which are expressed in Eq. (9).

3.1.3Collapse pressure model for UBD of horizontal wells

After the analysis of circumferential stresses of UBD in horizontal wells, collapse pressure models can be built up. Based on Biot's principle of effective stress and supposing that maximum principal stress, intermediate principal stress and minimum principal stress are σ Ϭ$f_{0\mathrm{max}}$ Ϭ$f_{0\mathrm{min}}$respectively in Eq. (9) when fluid seepage is considered (maximum principal stress, intermediate principal stress and minimum principal stress are (Ϭ $_{0\mathrm{max}}$ and Ϭ $_{0\mathrm{min}}$) sr respectively in Eq. (6) when fluid seepage is ignored). Two collapse pressure models for both conditions (whether fluid seepage is considered or not) can be established by substituting principal stresses into certain rock failure criterions. Then collapse pressures of different well structures and well trajectories (different inclination angles and relative azimuthal angles) can be derived. As MohreCoulomb criterion is one of the most used criterions, MohreCoulomb criterion is applied in this paper for establishing models and comparing the two models. MohreCoulomb criterion is:

$$\begin{cases} \sigma_r^f = P_{mud} - \alpha_e P_{mud} \\ \sigma_{\theta\max}^f = 0.5(\sigma_\theta + \sigma_z) + 0.5\sqrt{(\sigma_\theta - \sigma_z)^2 + 4\tau_{\theta z}^2} + \dfrac{r_e^2\left[2(1-v)\left(P_{op} - P_{mud}\right) + P_{op} - P_{mud}\right]}{\left(r_e^2 - R^2\right)(1-v)} - \dfrac{\left(P_{op} - P_{mud}\right)[2v-1]}{2(1-v)\ln(r_e/R)} - \alpha_e P_{mud} \\ \sigma_{\theta\min}^f = 0.5(\sigma_\theta + \sigma_z) - 0.5\sqrt{(\sigma_\theta - \sigma_z)^2 + 4\tau_{\theta z}^2} + \dfrac{r_e^2 v\left[2(1-v)\left(P_{op} - P_{mud}\right) + P_{op} - P_{mud}\right]}{(1-v)\left(r_e^2 - R^2\right)} - \dfrac{v\left(P_{op} - P_{mud}\right)[2v-1]}{2(1-v)\ln(r_e/R)} - \alpha_e P_{mud} \end{cases}$$

(9)

Chapter Four

Results and discussion

4.1 Data entry:

Item	Value	Unit
Original pore pressure coefficient	0.93	/
Radius of external boundary (re)	100	M
Borehole radius (R)	0.108	M
TVD of horizontal section	2514	M
Maximum horizontal stress (*σ* H)	1.8	Mpa/100 m
Minimum horizontal stress (*σ* h)	1.6	Mpa/100 m
Vertical stress (*σ* v)	2	Mpa/100 m
Poison's ratio (n)	0.23	/
Cohesion strength of the rock (C)	20.71	Mpa
Internal friction angle (φ)	34.5	Deg
Effective stress coefficient (àe)	0.9	/
equivalent densities of drilling mud (pm)	0.768	g/cm3

Table 4.1.1

4.3 Result

4.3.1 when I=90 α=90 θ=90

Tangential Stress (Mpa) FS	Tangential Stress (Mpa) FSN	Radial Distance (m)
84	70	0
75	60	0.5
70	55	0.7
63	50	1
58	45	1.5
47	40	2
32	30	3
30	30	4
30	30	6
30	30	8
30	30	10

Table 4.3.1

4.3.2 when I=90 α=90

Θ=(0,10,30,40,60,70,90,100,120,130,150,160,180)

R=0.1080 / 0.0762

ECD (r=0.108)	ECD (r=0.0762)	Ɵ
0.645	0.645	0
0.64	0.641	10
0.63	0.631	30
0.62	0.622	40
0.601	0.603	60
0.591	0.594	70
0.581	0.583	90
0.585	0.587	100
0.601	0.603	120
0.61	0.613	130
0.636	0.638	150
0.639	0.641	160
0.659	0.657	180

Table 4.3.2

4.4 Change of tangential stress with radial distance in both conditions

I=90 α=90 θ=90

Maximum ECD FS	Maximum ECD FSN	i
0.66	0.62	0
0.667	0.615	10
0.67	0.62	20
0.672	0.625	30
0.7	0.66	40
0.71	0.69	50
0.73	0.71	60
0.74	0.72	70
0.76	0.73	80
0.77	0.74	90

Fig. 4.3.3

Fig. 4.3.3 The changing trend of MECD with the inclination angle when a α (FS means the conditions with fluid seepage as a consideration, FSN means the conditions with fluid seepage not as a consideration).

Fig 4.4.1

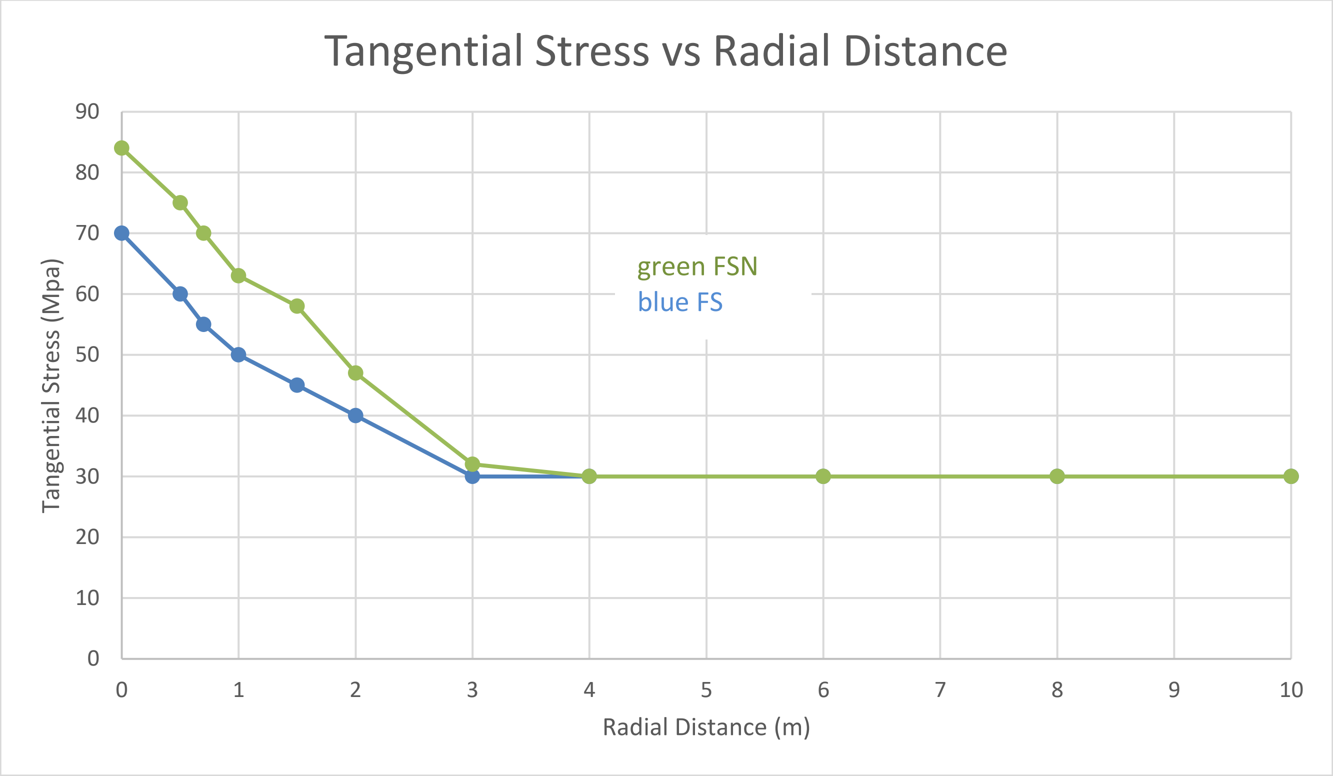


Fig. 4 shows, after putting the data in Table 1 into Eq. (2) (fluid seepage isn't considered) and the combining equation of Eqs(2) and (7) (fluid seepage is considered). It can be seen that the effects of fluid seepage reduces with the increase of radial distance, and the difference of tangential stresses in both conditions is small when r = 100 m, then re = 100 m is enough for wellbore stability analysis and can also avoid complex numerical modeling.

4.5 change of ECD with θ when borehole radius varies

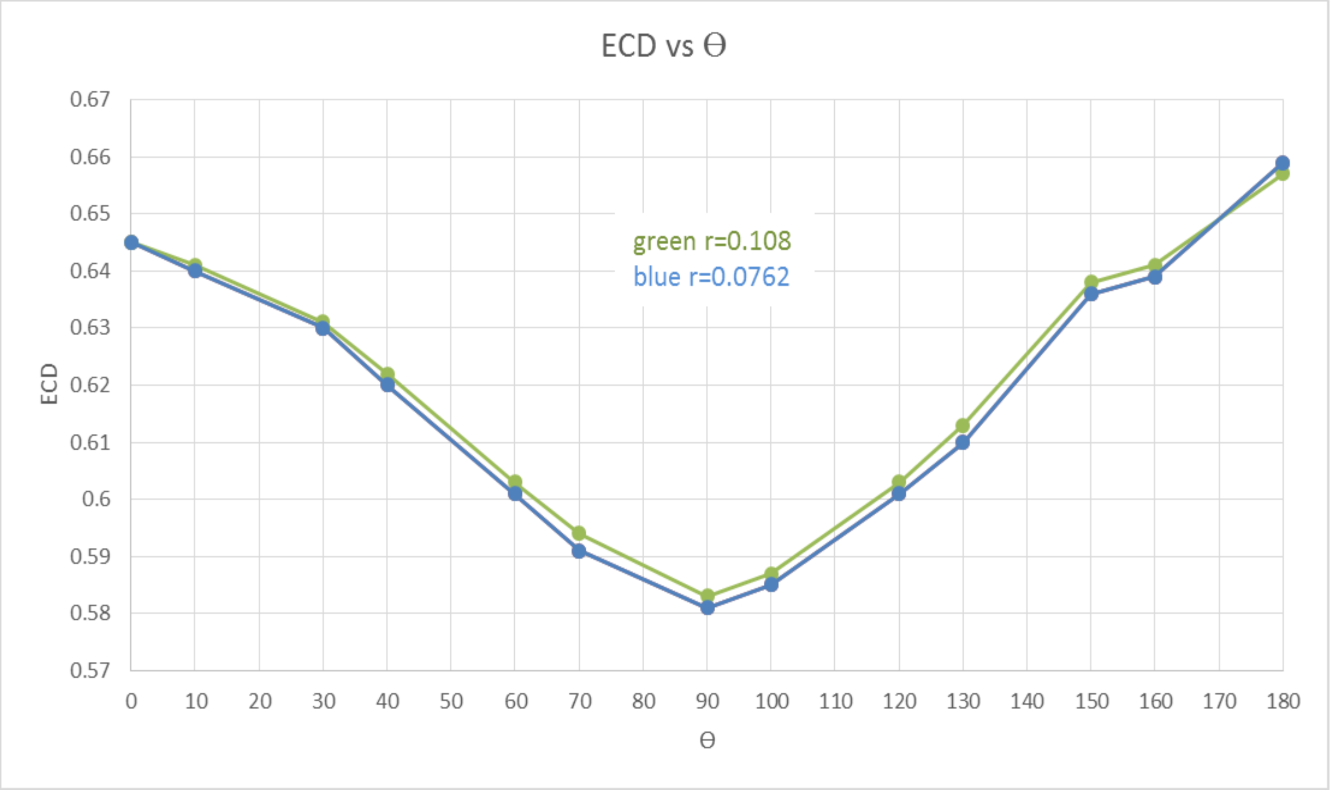
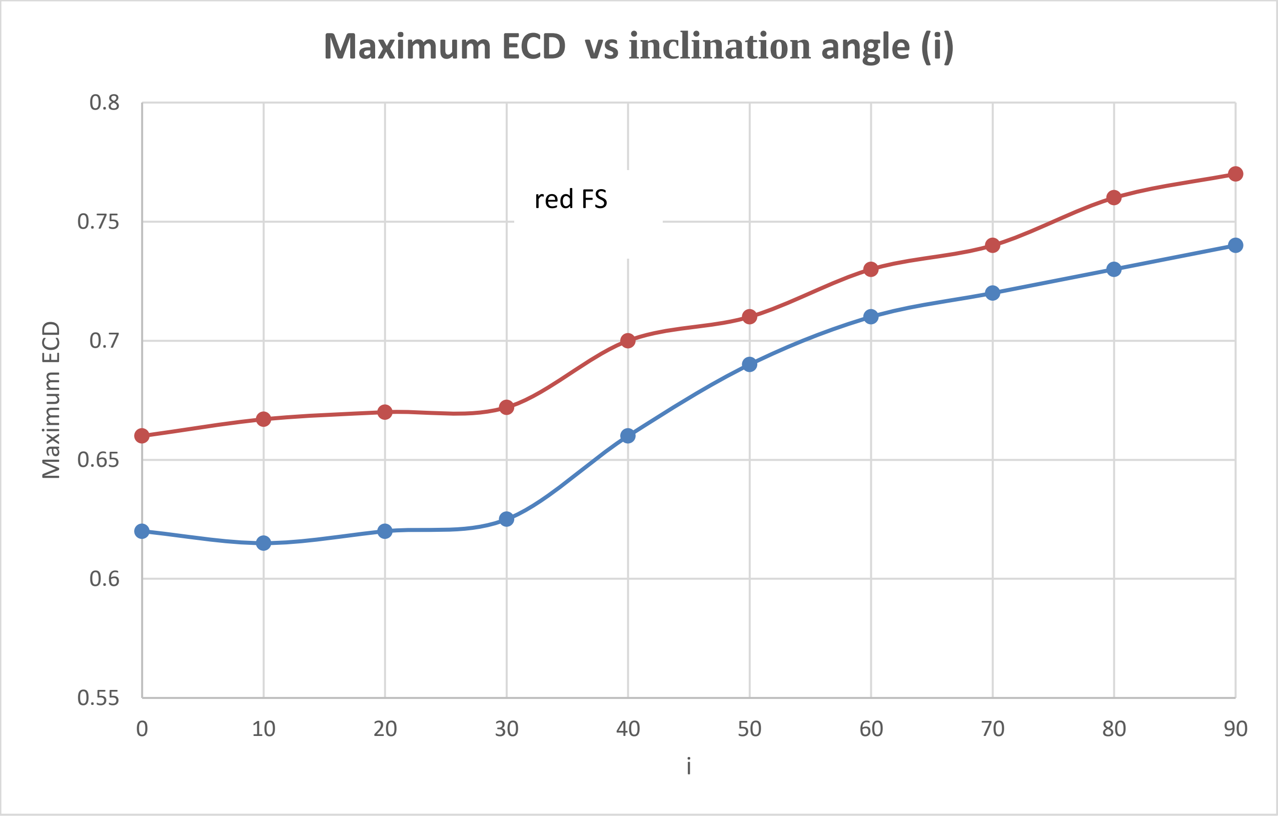


Fig. 6 displays the change of equivalent collapse density (ECD) with q when the inclination angle is 30_ and the relative azimuthal angle is 0_. It can be seen that ECD of R = 0.108 m is always greater than that of R = 0.0762 m, which means that ECD increases with the increase of borehole radius or that a slim hole is conducive to wellbore stability .



4.6 The impact of well structure on wellbore stability

While borehole radius is not taken as a parameter affecting wellbore stability in the conventional collapse pressure model, it is a parameter in the model considering fluid seepage. The influence of well structure on wellbore stability rests with the size of borehole radius. Two kinds of well structure applied in Daniudigas field are given in Fig. 5.In the analysis of the effect of borehole radius on wellbore stability, R =0.0762 m and R = 0.108 m are taken as the examples on the basis of the basic data inTable1.Fig.6displays the change of equivalent collapse density (ECD) with q when the inclination angles 30and the relative azimuthal angle is 0.It can be seen that ECD of R = 0.108 m is always greater than that of R=0.0762 m, which means that ECD increases with the increase of borehole radius or that a slim hole is conducive to wellbore stability

Chapter5

5.1Conclusions

By analyzing circumferential stresses, the collapse pressure model for UBD of horizontal wells with fluid seepage as a consideration is established, and by comparing it with the conventional model in which fluid seepage is ignored, the impact of well structure and well trajectory on wellbore stability and conclusions of the paper are approached as follows:

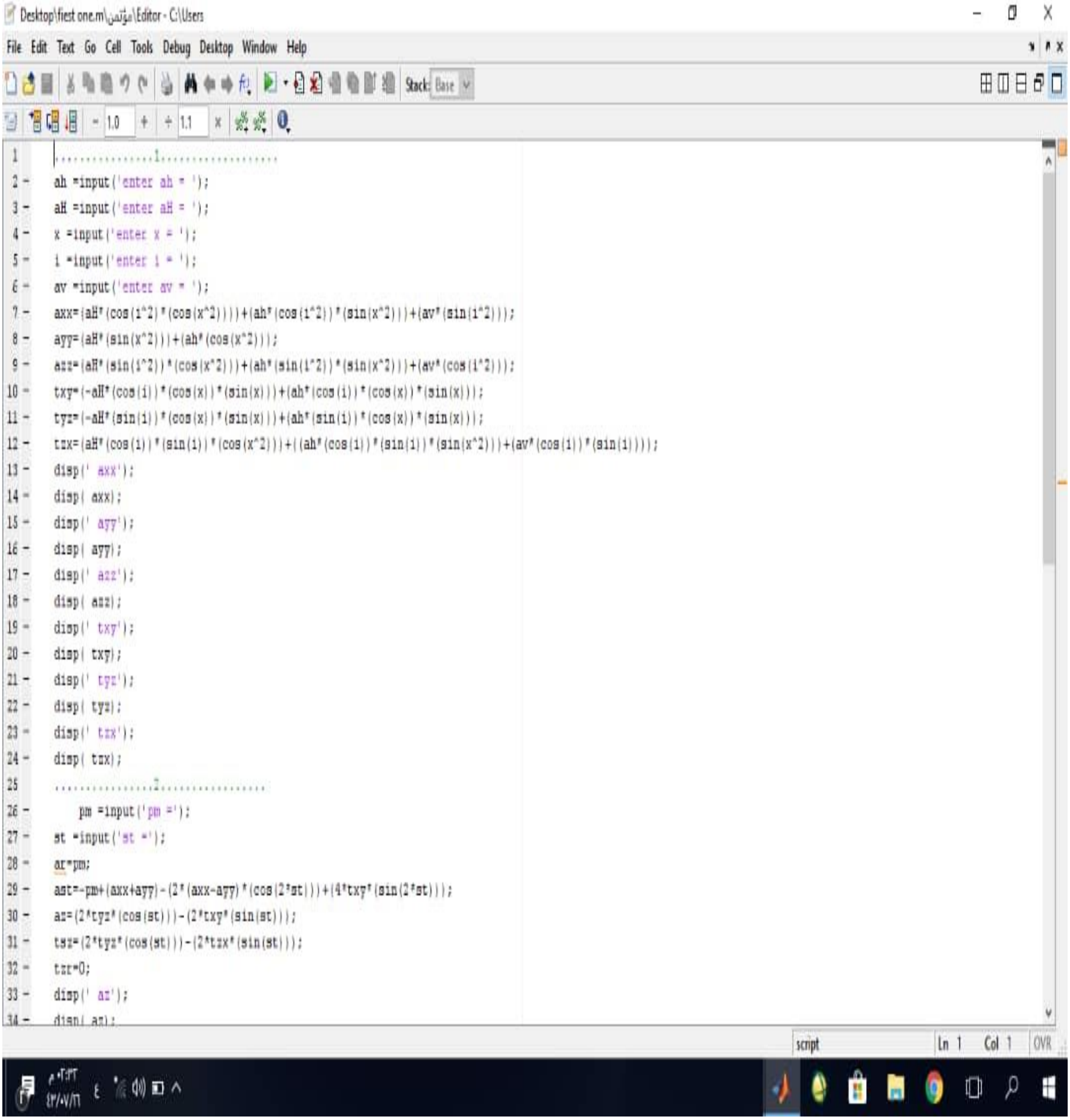
(1) The effects of well structure on wellbore stability are mainly embodied in the borehole radius ,which ,however, isn't taken into consideration in the conventional collapse pressure model. In our model, MECD reduces with the decrease of borehole radius, which indicates a broader mud weight window, and there by a more stable wellbore is obtained in a slim hole during UBD.

(2) With the change of the inclination angle, MECD with fluid seepage as a consideration is greater than MECD when fluid seepage is overlooked under a certain relative azimuthal angle, which means that the wellbore is more unstable with fluid seepage as a consideration. When a =90 and for both conditions (fluid seepage is considered and otherwise), MECD weakens with the increase of inclination angles at the beginning, while it eventually increases with the increase of the inclination angle; meanwhile, when a = 0 and for both conditions, MECD always increases with the increase of the inclination angle, i.e. wellbore will be more unstable at a higher inclination angle. The value of q where MECD is obtained reduces with the increase of the relative azimuthal angle, while the value of q will increase with the increase of the inclination angle, which will gradually reach 90.

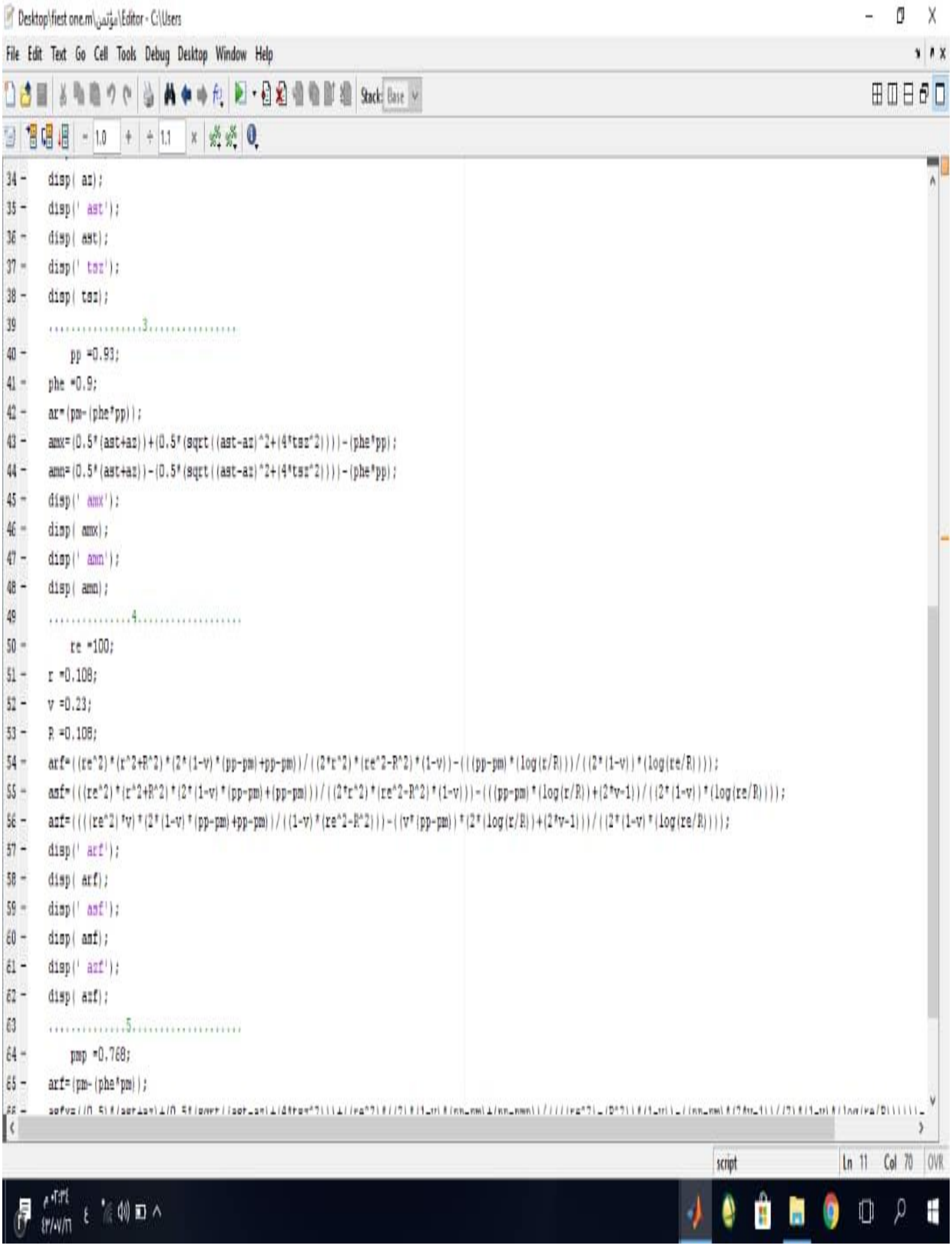
(3) When the relative azimuthal angle changes and the inclination angle is invariant, MECD considering fluid seepage is higher than MECD without considering fluid seepage; MECD of both conditions (fluid seepage is considered and otherwise) decreases with the increase of relative azimuthal angles (0/90) under a certain inclination angle (except for i = 0), which means a broader mud weight window and a more stable wellbore when σ =90. The changing trend of the value of q where MECD is obtained with relative azimuthal angles is the same for both conditions, and the value of q remains unchanged when i = 90.

Lab Index

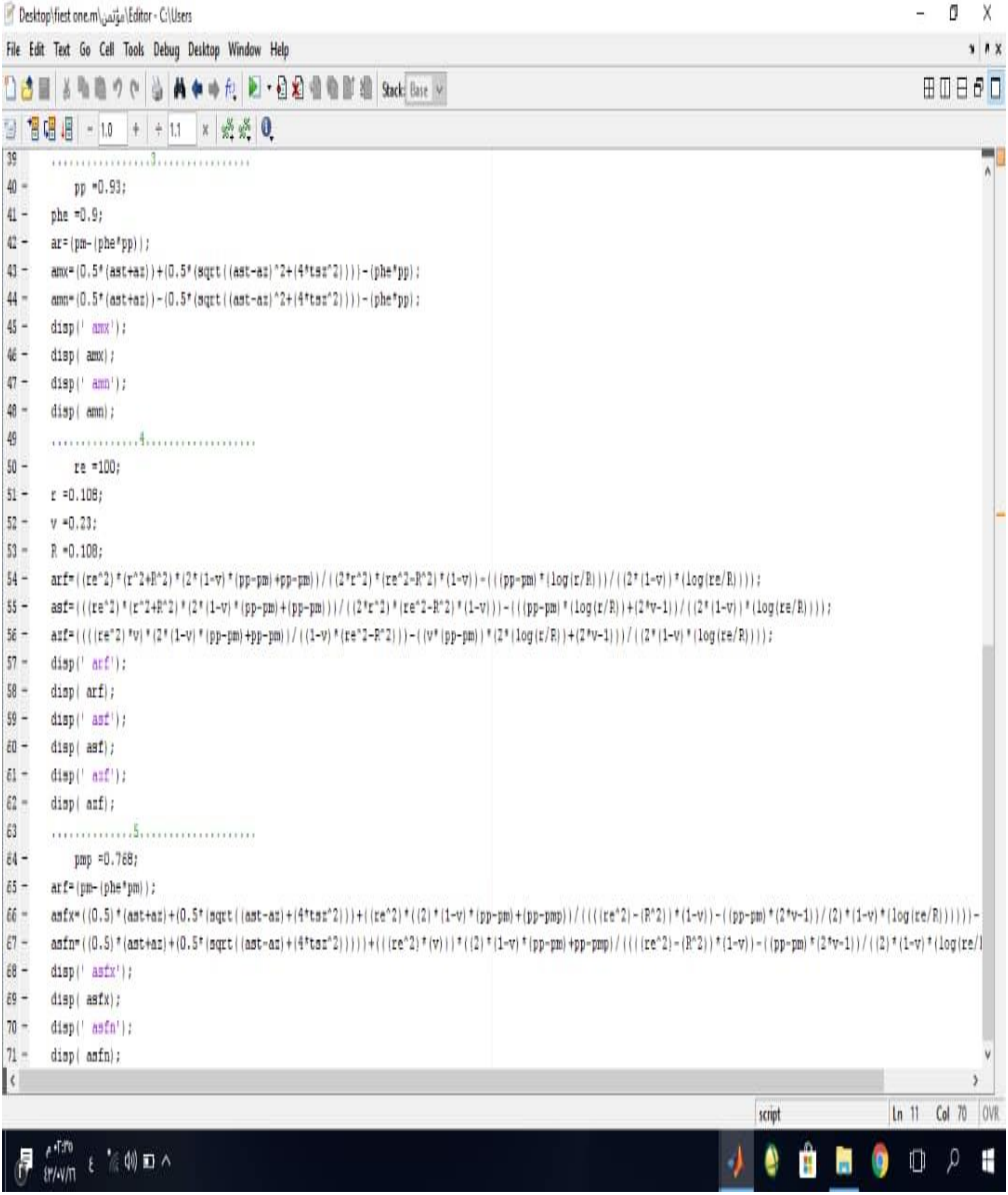
Matlab Equation



```
..................1....................
ah =input('enter ah = ');
aH =input('enter aH = ');
x =input('enter x = ');
i =input('enter i = ');
av =input('enter av = ');
axx=(aH*(cos(i^2)*(cos(x^2))))+(ah*(cos(i^2))*(sin(x^2)))+(av*(sin(i^2)));
ayy=(aH*(sin(x^2)))+(ah*(cos(x^2)));
azz=(aH*(sin(i^2))*(cos(x^2)))+(ah*(sin(i^2))*(sin(x^2)))+(av*(cos(i^2)));
txy=(-aH*(cos(i))*(cos(x))*(sin(x)))+(ah*(cos(i))*(cos(x))*(sin(x)));
tyz=(-aH*(sin(i))*(cos(x))*(sin(x)))+(ah*(sin(i))*(cos(x))*(sin(x)));
tzx=(aH*(cos(i))*(sin(i))*(cos(x^2)))+((ah*(cos(i))*(sin(i))*(sin(x^2)))+(av*(cos(i))*(sin(i))));
disp(' axx');
disp( axx);
disp(' ayy');
disp( ayy);
disp(' azz');
disp( azz);
disp(' txy');
disp( txy);
disp(' tyz');
disp( tyz);
disp(' tzx');
disp( tzx);
..................2..................
    pm =input('pm =');
st =input('st =');
ar=pm;
ast=-pm+(axx+ayy)-(2*(axx-ayy)*(cos(2*st)))+(4*txy*(sin(2*st)));
az=(2*tyz*(cos(st)))-(2*txy*(sin(st)));
tsz=(2*tyz*(cos(st)))-(2*tzx*(sin(st)));
tzr=0;
disp(' az');
disp( az);
```



```
disp( az);
disp(' ast');
disp( ast);
disp(' tsz');
disp( tsz);
.................3................
   pp =0.93;
phe =0.9;
ar=(pm-(phe*pp));
amx=(0.5*(ast+az))+(0.5*(sqrt((ast-az)^2+(4*tsz^2))))-(phe*pp);
amn=(0.5*(ast+az))-(0.5*(sqrt((ast-az)^2+(4*tsz^2))))-(phe*pp);
disp(' amx');
disp( amx);
disp(' amn');
disp( amn);
...............4...................
   re =100;
r =0.108;
v =0.23;
R =0.108;
arf=((re^2)*(r^2+R^2)*(2*(1-v)*(pp-pm)+pp-pm))/((2*r^2)*(re^2-R^2)*(1-v))-(((pp-pm)*(log(r/R)))/((2*(1-v))*(log(re/R))));
asf=(((re^2)*(r^2+R^2)*(2*(1-v)*(pp-pm)+(pp-pm)))/((2*r^2)*(re^2-R^2)*(1-v)))-(((pp-pm)*(log(r/R))+(2*v-1))/((2*(1-v))*(log(re/R))));
azf=((((re^2)*v)*(2*(1-v)*(pp-pm)+pp-pm))/((1-v)*(re^2-R^2)))-((v*(pp-pm))*(2*(log(r/R))+(2*v-1)))/((2*(1-v)*(log(re/R))));
disp(' arf');
disp( arf);
disp(' asf');
disp( asf);
disp(' azf');
disp( azf);
..............5....................
   pmp =0.768;
arf=(pm-(phe*pm));
```



```
    ..................3................
        pp =0.93;
    phe =0.9;
    ar=(pm-(phe*pp));
    amx=(0.5*(ast+az))+(0.5*(sqrt((ast-az)^2+(4*tsz^2))))-(phe*pp);
    amn=(0.5*(ast+az))-(0.5*(sqrt((ast-az)^2+(4*tsz^2))))-(phe*pp);
    disp(' amx');
    disp( amx);
    disp(' amn');
    disp( amn);
    ...............4....................
        re =100;
    r =0.108;
    v =0.23;
    R =0.108;
    arf=((re^2)*(r^2+R^2)*(2*(1-v)*(pp-pm)+pp-pm))/((2*r^2)*(re^2-R^2)*(1-v))-(((pp-pm)*(log(r/R)))/((2*(1-v))*(log(re/R))));
    asf=(((re^2)*(r^2+R^2)*(2*(1-v)*(pp-pm)+(pp-pm)))/((2*r^2)*(re^2-R^2)*(1-v)))-(((pp-pm)*(log(r/R))+(2*v-1))/((2*(1-v))*(log(re/R))));
    azf=((((re^2)*v)*(2*(1-v)*(pp-pm)+pp-pm))/((1-v)*(re^2-R^2)))-((v*(pp-pm))*(2*(log(r/R))+(2*v-1)))/((2*(1-v)*(log(re/R))));
    disp(' arf');
    disp( arf);
    disp(' asf');
    disp( asf);
    disp(' azf');
    disp( azf);
    ..............5....................
        pmp =0.768;
    arf=(pm-(phe*pm));
    asfx=((0.5)*(ast+az)+(0.5*(sqrt((ast-az)+(4*tsz^2)))+((re^2)*((2)*(1-v)*(pp-pm)+(pp-pmp))/((((re^2)-(R^2))*(1-v))-((pp-pm)*(2*v-1))/(2)*(1-v)*(log(re/R)))))-
    asfn=((0.5)*(ast+az)+(0.5*(sqrt((ast-az)+(4*tsz^2)))))+(((re^2)*(v)))*((2)*(1-v)*(pp-pm)+pp-pmp)/((((re^2)-(R^2))*(1-v))-((pp-pm)*(2*v-1))/((2)*(1-v)*(log(re/
    disp(' asfx');
    disp( asfx);
    disp(' asfn');
    disp( asfn);
```

References

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