1. Introduction

Automated drilling is a hot topic in the current Oil/Gas industry. Efforts at automation are being undertaken by numerous organizations with objective of producing more efficient drilling; in this way, automated drilling may be of great benefit in today's market with dwindling reserves and increasing exploration activity (Iversen *et al.* 2013).

Zamora & Geehan (2013), Wessling *et al*. (2012), Cayeux *et al.* (2012) and Wessling *et al.* (2011 a, b) made attempts to discover the various aspects of automated drilling. An automatic evaluation of the wellbore stability is one of the most significant tasks necessary for carrying out automated drilling.

Wellbore instability is a continuing problem, which accounts for a significant amount of unproductive time and results in substantial annual expenditure for the petroleum industry. The causes of wellbore instability can be classified into uncontrollable and controllable factors (Pašić *et al.* 2007). Table 1 lists the causes of wellbore instability after Pašić *et al.* (2007).

Table 1 Causes of wellbore instability (Pašić *et al.* 2007)

Uncontrollable factors	Controllable factors
Naturally fractured or faulted formations	Bottomhole pressure (mud pressure)
Tectonically stressed formations	Well inclination and azimuth
High in-situ stresses	Transient pore pressures
Mobile formations	Physical/chemical rock-fluid interaction
Unconsolidated formations	Drill string vibrations
Naturally over-pressured shale collapse	Erosion
Induced over-pressured shale collapse	Temperature

1.1. Objectives

This thesis focuses on solutions for calculating one of the controllable factors (the mud pressure window) when carrying out automated drilling. Two terminologies must be explained, mud pressure window and mud pressure gradient window. The mud pressure window is an allowable mud pressure range to maintain the borehole stability, whose unit is MPa. The mud pressure gradient window is calculated by dividing the mud pressure window by the depth, whose unit is KPa/m. In this thesis, the "mud pressure gradient window" was abbreviated to "mud window". The mud window should be determined at the pre-drilling phase and be updated during drilling in real-time based on the continuing data input from the surface logging systems, including Logging While Drilling (LWD) and Measurement While Drilling (MWD) after Wessling *et al.* (2012). The objectives of this thesis are on the one hand to develop models to calculate FG, SFG, and RTFG and on the other hand to develop methods to determine the needed input parameters using data from the LWD or MWD systems. The THM-coupled effect during drilling was another subject of investigation by this thesis because of a growing number of deep wells drilled today.

1.2. State-of-the-art

Currently, most of the methods proposed have analysed borehole stability in the pre- or post-drilling phase (called pre- and post- methods in this thesis) and the vast majority of these theories and methods have also been carried out by many authors (in the pre- or post- drilling phase)

Liz-Losada & Alejano (2000), Chen *et al.* (1997), Moos *et al.* (2003), Fjær *et al.* (1992) and Pašić *et al.*(2007), for example, determined the mud pressure window necessary to avoid tensile and compression failures of the wellbore in the pre- or post-drilling phase. Moos *et al.* (2003) carried out an especial probabilistic analysis (quantitative risk analysis) to investigate wellbore stability and further to determine mud pressure window.

There is also a number of borehole stability analytic software for the optimization of drilling projects e.g. BOREHOLE (Braun 2014), PBORE-3D (IPF 2013) etc. Numeric software (e.g. FLAC3D) have also been employed to compute stress distributions around a borehole and further analyse borehole stability (Zinchenko *et al.* 2006 & Luo 2010 a).

All of the pre- or post- methods needed various input data. The most frequent of which were in-situ stresses, pore pressure and rock compressive strength, which were normally measured in the laboratory or assumed. These parameters were also computed using seismic data. Zinchenko *et al.* (2006) used 3D seismic data for mapping significant input parameters to predict the wellbore stability. FLAC3D was employed by Zinchenko *et al.* (2006) to analyse the borehole stability numerically.

Efforts have also been made to carry out a borehole stability analysis in real-time during drilling. However, the key point is how to determine the necessary input data in real-time correctly and reliably. Determination of the necessary input parameters using logging data therefore becomes crucial to carry out a borehole stability analysis in real-time. Although a number of articles presented methods or models for analysing the borehole stability in real-time, these methods still needed various input data from laboratory measurements as well as assumptions. The software PBORE-3D can be used to analyse and simulate the time-dependent effects on wellbore stability while drilling. It can also estimate a safe mud window in real-time (IPF 2013). However, according to Abousleiman *et al.* (1997), the input parameters (in-situ stresses, pore pressure and rock tensile and compressive strength) must be given to the software as they cannot be determined by PBORE-3D in real-time.

Some input parameters could already be determined in real-time. The rock compression strength (UCS) was frequently determined during drilling using logging data. Hareland *et al.* (1996) developed software to predict a safe mud pressure window in the pre- and post-drilling phase as well as during drilling. The compressive strength was calculated while drilling using logging data. Similarly, Lang *et al.* (2011) developed models to analyse the wellbore stability in real-time. They used sonic logs to compute the UCS while drilling. Similar calculations were also undertaken by Sayers *et al.* (2009), Chang *et al.* (2006), etc.

The vertical in-situ stress is another significant input parameter, which can be relatively easily determined in real-time. The vertical in-situ stress was normally computed based on density logs (Sayers *et al.* (2009), Lang *et al.* (2011), Zinchenko *et al.* (2006) etc.).

The two horizontal stresses are the most significant parameters, which affect borehole stability (Moos *et al.* (2003) and Chen *et al.* (1997)). However, a number of "during drilling methods" determined the two horizontal stresses based on assumptions or empirical equations. Hareland *et al.* (1996) calibrated in-situ stresses using the compressive strength. However the two horizontal stresses were assumed be identical. Lang *et al.* (2011) determined the minimum horizontal stress using a uniaxial strain model. The maximum horizontal stress was however calculated using an empirical equation. Several other significant input parameters that were seldom discussed the previous articles, e.g. Biot's coefficient, the internal friction angle as well as the cohesion.

In deep drilling, thermal effects significantly influence the borehole stability. Chen *et al.* (2003), Li (1998), Tang & Luo (1999) and Hou & Luo (2011) investigated the thermal effect on the borehole stability. They all analysed the time-dependent borehole stability. However, the mud temperature at the borehole wall was assumed to be constant. During drilling the mud temperature during drilling is however not constant but varies with the mud circulation. Moreover, they all calculated the temperature distribution numerically, which was time-consuming. Therefore, analysing the borehole stability in real-time, considering the thermal effects, becomes difficult.

1.3. Thesis subjects

Considering the above discussed challenges to carry out a calculation of a suitable mud pressure window under HM- and THM-coupled conditions in real-time (Chapter 1.2), this thesis not only focuses on model development for determination FG, SFG, and RTFG, but also on the methods to determine or estimate the significant input parameters (including PPG, MHSG, and VSG) using well logging data.

In Chapter 2, six boundaries were employed to determine the mud pressure windows: FG, SFG, PPG, MHSG, RTFG, and VSG. The criterion determining the FG, SFG and RTFG were developed in this chapter. PP, VSG, and MHSG are input parameters, which are discussed in later chapters.

In Chapter 3, because measuring the input parameters simultaneously is extremely complicated, if not impossible, during drilling, a sensitivity analysis was performed to categorize the input parameters based on their effects on the mud window. Some parameters build the boundaries to determine the mud window, which were categorized in the "must-have" group. The parameters which have relatively higher effects were categorized in "high-sensitive" group, while parameters which have relatively low effects were categorized in "low-sensitive" group.

In Chapter 4, the existing methods or correlations to calculate PPG, UCS and IFA using logging data were analysed and evaluated by literature study.

Chapter 5 presents two methods for determining in-situ stresses using logging data. The first method calculates the in-situ stresses by analysing the borehole shape. The second method calculates the in-situ stresses based on anisotropic loading and the induced shear wave splitting.

In Chapter 6, three methods were developed for calculating Biot's coefficient using logging data. The first method calculates Biot's coefficient using the existing empirical relations between porosity and Biot's coefficient. The second method calculates Biot's coefficient using dynamic rock and solid compressibility. The solid shear and compressive velocity (V_s and V_p) are calculated using the newly developed equations, which describes the relationship between differential pressure, porosity and the wave velocity of sandstone. The third method also calculates Biot's coefficient using dynamic rock and solid compressibility but the solid wave velocities are computed based on the significant finding that the trend of the V_p/V_s ratio with respect to S-wave velocity is constant for sediments including over pressured sand.

Chapter 7 presents the developed semi-analytical method, which can simulate the depth-dependent temperature profile in the tubing, annulus and rock formations surrounding the borehole. The simulated results will be used in real-time to calculate a suitable mud pressure window.

In Chapter 8, two case studies were performed to explain all the developed solutions to determine suitable mud windows. The influence of the thermal effects was investigated by comparing the width of the mud pressure window under HM- and THM-coupled conditions

2. Models to calculate a suitable mud window

This thesis tried to find solutions to update a suitable mud window in real-time considering the HM- and THM-coupled effects. The study developed software ***REDMW*** (***RE****al-time* ***D****etermination of* ***M****ud* ***W****indow*) served to calculate a suitable mud pressure window both in the pre-drilling phase as well as during drilling. Figure 1 shows the basic principle needed to calculate a mud window in real-time. Firstly, various data were inputted into the developed software ***REDMW***. Then the software calculated a suitable mud window based on the input data and downhole conditions. If the mud density exceeds the allowable mud window, an alarm will be triggered. The input data came from three sources, data bank, operation data and measurement/logging while drilling.

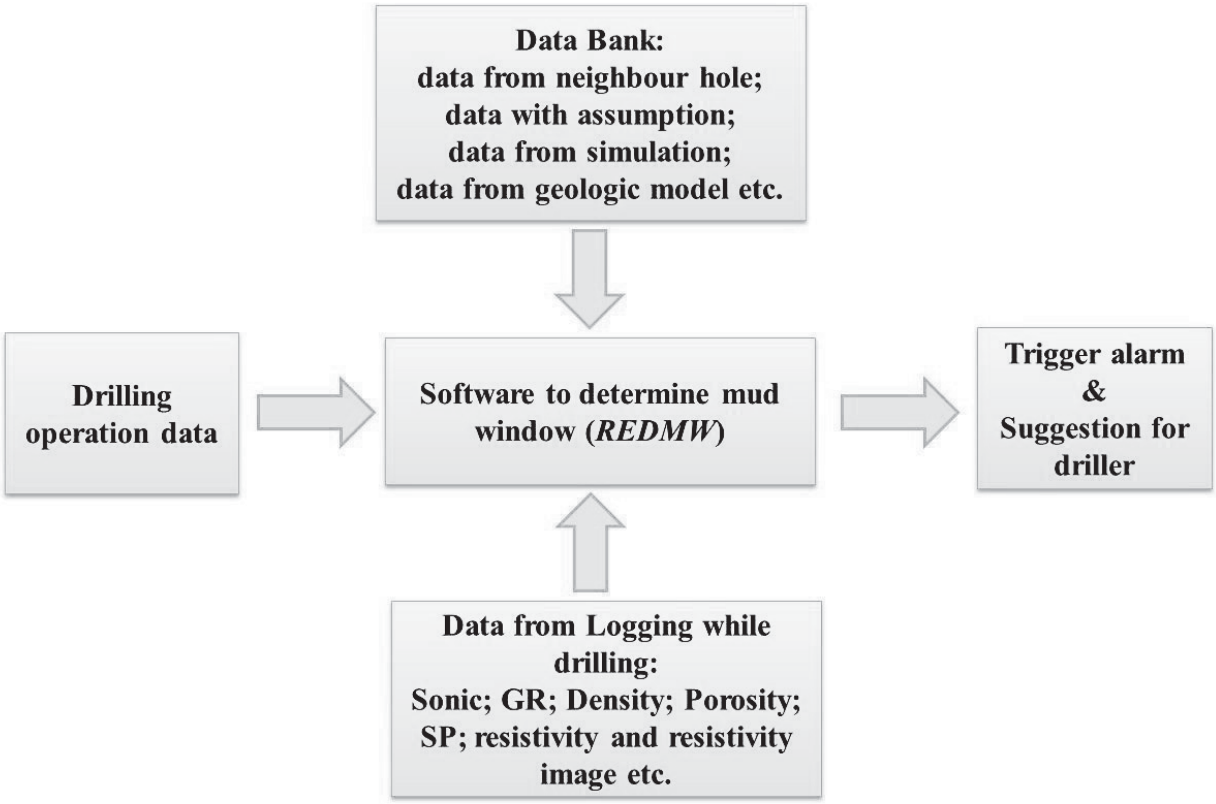

Figure 1 Principle to update a suitable mud pressure window in real-time

As shown in Figure 2 the wellbore stability is maintained if the mud pressure gradient stays within the calculated mud window. Six boundaries build the upper and lower ranges of the mud window: FG, SFG, PPG, MHSG, RTFG, and VSG, which should be determined during drilling using logging data. Because PPG, MHSG, and VSG are input parameters the main task of this thesis should be on one hand to develop models to calculate FG, SFG, and RTFG of different rocks under distinctive downhole conditions, and on the other hand to develop methods to determine or estimate the important input parameters correctly, reliably as well as in real-time. These functions were carried out by the software ***REDMW***. The software ***REDMW*** has two main modules, the mud window module and the input parameters module (Figure 3). The "other modules" serve the two major modules. The "mud window module" serves to calculate a suitable mud pressure window in real-time as well as in the pre-drill phase. The "input parameters module" serves to calculate important input parameters with data from the LWD or the MWD.

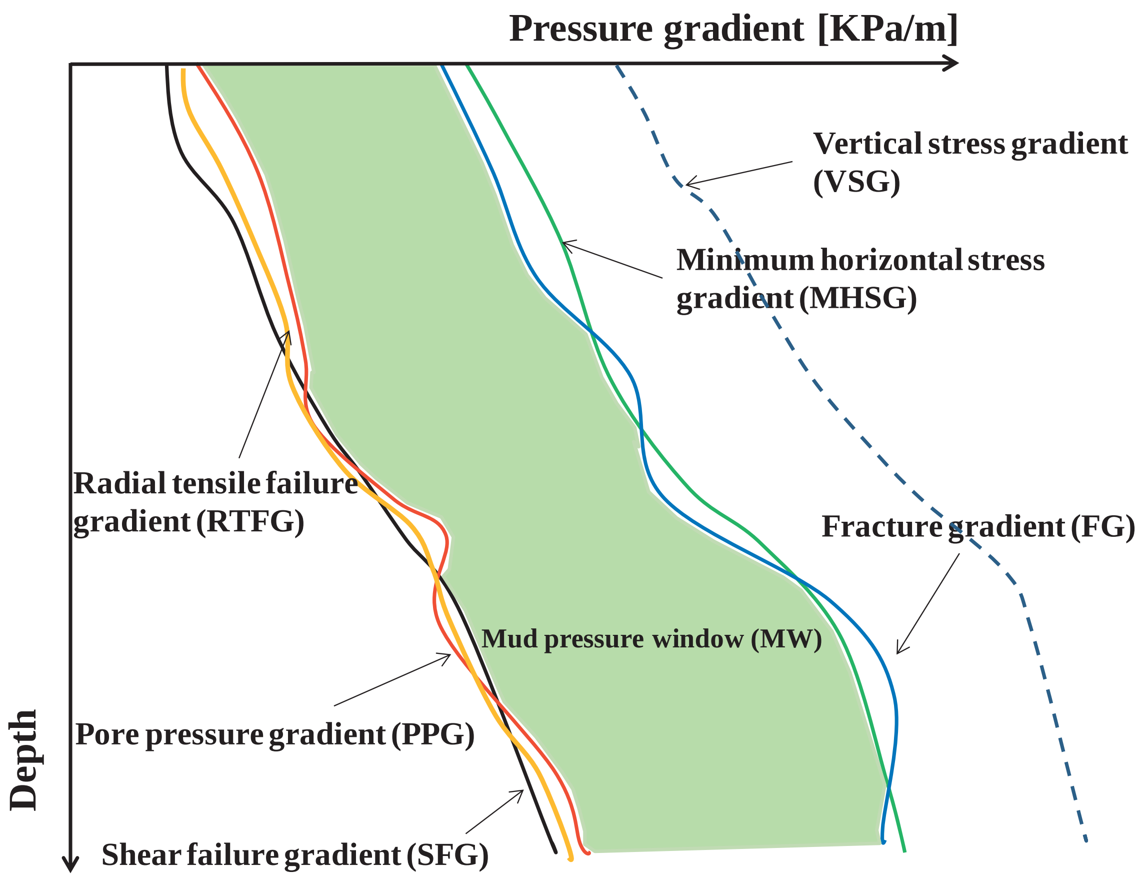

Figure 2 Boundaries determining a suitable mud window

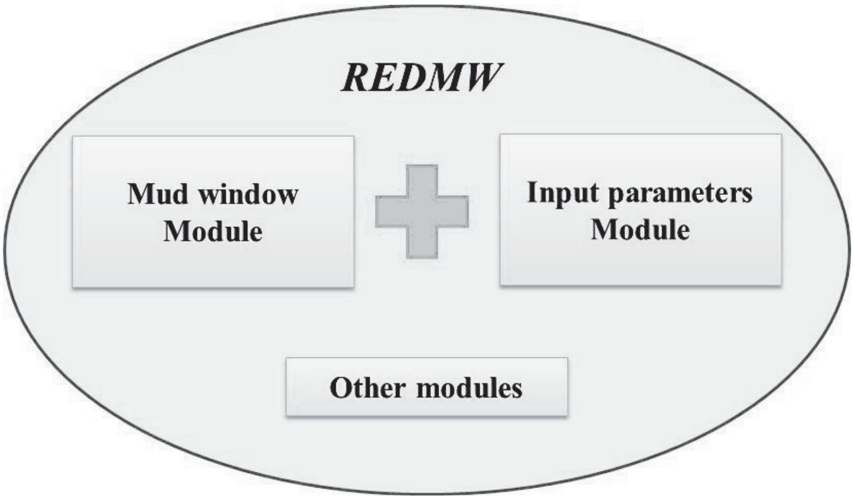

Figure 3 Models involved in the study developed software *REDMW*

The wellbore failure mechanisms have been investigated by many authors (Chen *et al.* 1997, Braun *et al.* 1992, Moos *et al.* 2003, Fjær *et al.* 1992 and Pašić *et al.* 2007). The failures can be classified into two types, compressive and tensile failures. The compressive failures (shear failures) happen if there is not enough support from the drilling fluid (mud). The compressive failures will induce wellbore breakout (brittle rocks) or hole size reduction (soft rocks), which will further result in the collapse of the wellbore. Figure 4 shows the compressive failures in the brittle and soft rocks. Therefore the shear failure gradient (SFG) builds one of the lower boundaries of the suitable mud window (Figure 2).

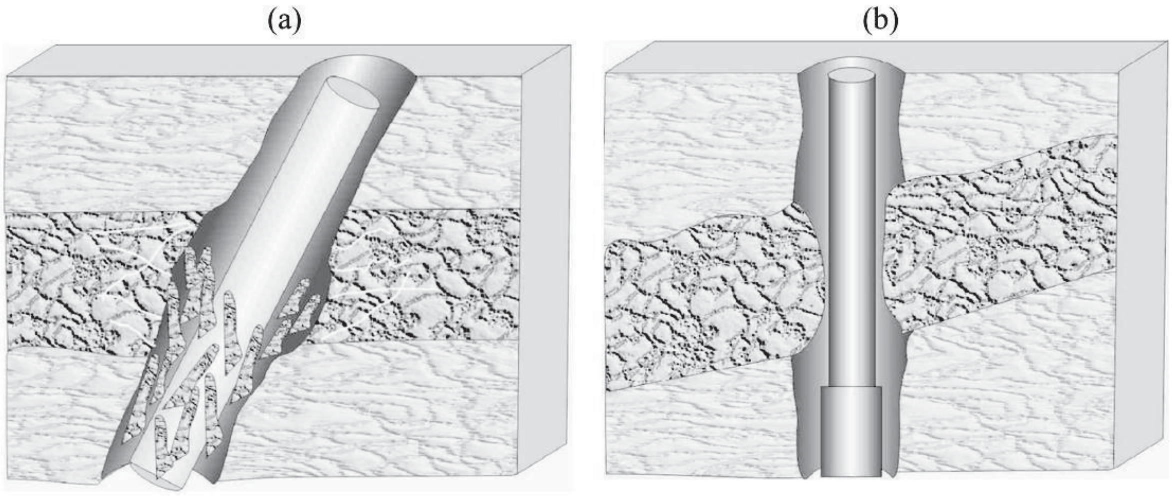

Figure 4 Wellbore compressive failures in brittle rocks (a) and soft rocks (b) after Pašić *et al.* (2007)

Tensile failures are induced by high or low mud pressure, which increase the risk of lost circulation. Because of the initiation and propagation of tensile failures, a significant amount of mud is lost into the formation (Moos *et al.* 2003). There are three types of tensile failures: vertical, horizontal and radial tensile failures. Figure 5 shows a sketch of vertical tensile failures, which are induced by tangential tensile stress in the rocks surrounding the wellbore. The tangential tensile stress is the result of a too high mud pressure gradient. Therefore, the so called fracture gradient (FG) builds one of the upper boundaries.

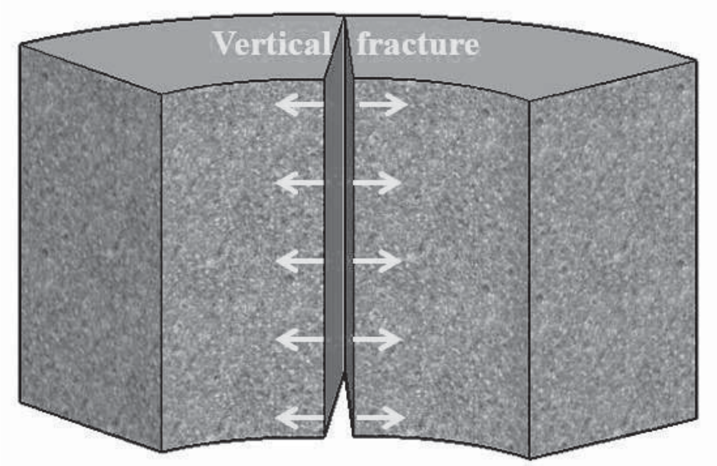

Figure 5 Vertical tensile failure at borehole wall

In the E&P industry the fracture gradient (FG) is normally assumed to be equal to the minimal horizontal stress gradient (MHSG), which according to the thesis calculations is only valid under dry conditions (rock tensile strength= zero). Despite this, the MHSG also builds another upper boundary in this thesis considering the E&P experience**.**

When the vertical tensile stress is bigger than the rock tensile strength, horizontal tensile failure is induced (Figure 6). Normally the rock tensile strength is approximately equal to zero. Therefore, if the mud pressure gradient is bigger than the vertical stress gradient (VSG), horizontal tensile failure is induced. The vertical stress gradient (VSG) thus builds one of the upper boundaries. Except in the compressive stress regime ($\sigma_H > \sigma_h > \sigma_V$), the VSG is bigger than the MHSG (another upper boundary), which has therefore no influence on the mud window. The VSG should only be considered when the minimum horizontal stress is bigger than the vertical stress (compressive stress regime).

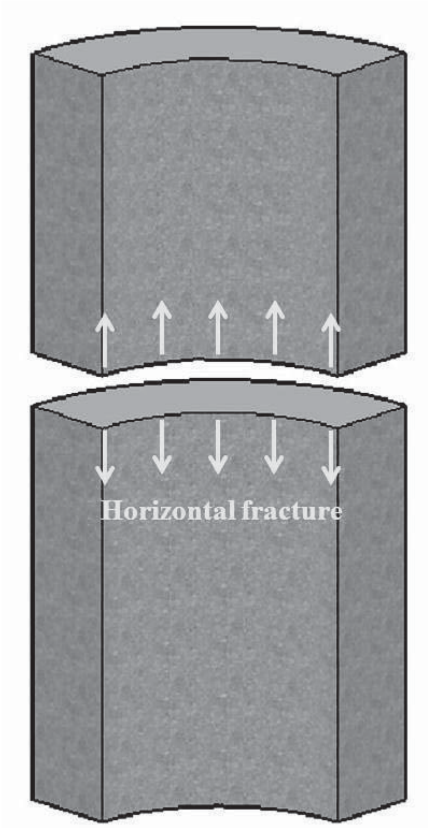

Figure 6 Horizontal tensile failure at the borehole wall

Pašić *et al.* (2007) discussed the radial tensile failure in the near field of a borehole but did not investigate the building mechanism. According to the calculation in Chapter 2.2.1, it has been found that if the mud pressure is too small, tensile radial stress is induced in the vicinity around the borehole under undrained condition. The so called radial tensile failure gradient (RTFG) defined in this thesis, (explained in Chapter 2.2.1), builds one of the lower boundaries.