MUD-WEIGHT PREDICTION FOR OFFSHORE DRILLING

by

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the requirements for the

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CERTIFICATION OF APPROVAL

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Approved by,

____

(William Pao)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

MAY 2012

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

(MUHAMAD FARIS BIN ALI OSMAN)

ABSTRACT

Selecting a proper mud-weight during drilling is important to prevent wellbore breakout. Through development of computer software, the optimum range of mud-weight can be computed by trial-and-error using finite element elasto-plastic model. Even though the results are very accurate and precise, inherited parameter uncertainties associated with the vertical to horizontal earth stress ratios, frac-gradients, Coulomb friction angle and cohesion means the precision attained in such software is meaningless and could be misleading to field engineers working on site. An even more pressing problem to the drilling manager is that these software are too specialist oriented and required input parameters that are not available practically in a day-to-day operation to make in-situ decision. The idea behind this project is to propose a new workflow of mud-weight prediction that does not require a precise input of parameters and develop a simple prototype lab-version program that could be used in-house.

ACKNOWLEDGEMENTS

First and foremost, I would like to extend my gratitude to my supervisor, Dr William Pao, who had been assisting, encouraging and supporting me in completing my final year project. I sincerely appreciate all the guidance and knowledge that had being given to me. Moreover, his kind co-operation truly helps me in understanding the problem and solving the complexities that occurred during the timeframe of this project.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1: INTRODUCTION

1.1 Project Background

Borehole instability is a major obstacle to quick and cost-efficient drilling. Borehole instability and borehole failure in shales is considered the major cause of loss in time and cost during drilling. Borehole problems cost implied to oil and gas industry worldwide are estimated to be around 400 to 500 Million USD per year [1]. Unexpected or unknown behavior of rock is often the cause of drilling problems, resulting in an expensive loss of time and cost. Also there is high risk of losing part or even whole borehole. Thus, many efforts had been put worldwide by engineers and researchers to improve the drilling fluid programs, casing programs, and operating procedures in drilling a well to minimize borehole instability problems.

1.2 Problem Statement

Borehole instability develop with time, starting with the fragmentation of the borehole wall, followed by transfer of the fragments to the annulus and finally, if the hole cleaning is insufficient, it will lead to problems such as tight hole, stuck-pipe, excessive solid production, increased circulating pressure and many more [2]. The ultimate consequences of borehole instability are having to side-track or losing the hole completely.

One of the effective ways to prevent and cure borehole instability problem is by controlling the mud weight used in the drilling process. By optimizing the mud pressure and mud composition, the borehole stability can be achieved. Mud used in the drilling process will create mud cake that will balance the pressure in the borehole. When a good mud cake is formed, the mud does not invade the formation and the pore pressure remains undisturbed [3]. Mud weight used must be selected properly. Safe mud weight window must be determined before applied to the borehole. If the mud pressure is lower than the formation pore pressure, the borehole will collapse. Else, if the mud pressure exceeds the formation strength, it will result to fracture propagation at the wall of the borehole [4].

1.3 Objectives

The objectives of this project are:

a) Solve the governing equation to determine the stress distribution around the borehole.
b) Define failure criteria of a borehole.
c) Develop a mathematical model for estimating a safe mud window to maintain borehole stability.
d) Develop computer software based on the model with appropriate Graphical User Interface (GUI) which will allow the model to be easily used by drilling engineers in site. The software should be able to relate all required parameters for borehole stability such as in-situ stresses, hole angle, hole direction, rock strength, and mud weight on the stability or instability of the borehole.

1.4 Scope of Study

The general scope of this study is to develop a program that is able to estimate the borehole stability in order to allow efficient drilling process. The earth formation is portrayed as finite element elasto-plastic model to predict the stress concentration, which greatly influence the borehole stability. The specific scopes are: identifying stresses that exist in the underground formation; conducting study on rock failure condition; develop mathematical model for calculating stress distribution around borehole in local cylindrical coordinate system, develop mathematical model for calculating mud weight range which depends on the stress distribution value and rock properties; and last but not least, implement the mathematical model into a computer software which can be used by drilling engineers in site.

1.5 Feasibility of the Project

The project is estimated to be completed within a period of 8 months (2 semesters). All equipment and tools needed to perform this project are readily available in authors Personal Computer. With all the resources provided, this project can be considered as a feasible project within the time frame given.

CHAPTER 2: LITERATURE REVIEW

2.1 Wellbore Failure

Wellbore instability is a very common problem in many oil fields all over the world which has not been sufficiently solved up to now [6]. Ensuring wellbore stability will provide a substantial effect towards drilling process. In addition to the costs associated with wellbore stability while drilling, wellbore stability has a significant impact on production problems [4]. For example, the ability to drill gauge holes would have a significant impact in production operations as follows [4]:

1) Improved cementing, which resulting in fewer squeezes and better zonal isolation.
2) Improved sand control performance as a result of improved cementing.
3) Reduced perforating problems due to thick cement sheaths, thus higher productivity.
4) Improved log response and thus better evaluation.

Borehole failure can be grouped into three classes [4]:

i. Hole size reduction due to the plastic flow of the rock into the borehole. Symptoms of this condition are repeated requirements of reaming to bottom and in extreme conditions lead to stuck pipe.
ii. Hole enlargement due to rock failing in a brittle manner and falling into the borehole (sloughing shale). Problems resulting from hole enlargement include fill on trips, poor directional control, and poor cementing.
iii. Fracturing due to the tensile splitting of the rock from excessive well bore pressure. Severe loss of drilling fluid to the formation from fracturing causes lost in time and costs.

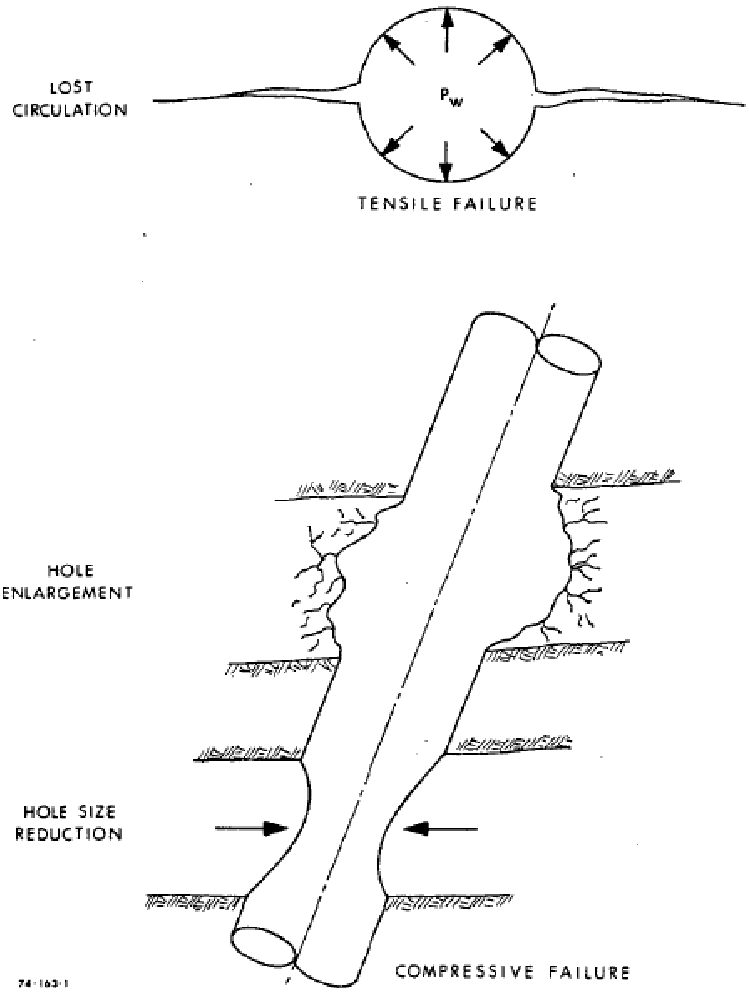

Figure 2.1: Types of borehole failure [4]

Since a long time ago, research and efforts have been put to apply the existing knowledge of solid mechanics to improve current methods for predicting and controlling borehole failures. Analysis based on elasticity and a Mohr–Coulomb failure criterion for the rock has been traditionally used to predict borehole failure. To calculate whether a borehole is stable or unstable, three things are required [4]:

1) An analytic model of the borehole (equations to calculate the stresses around the borehole).
2) Input parameters to the model (in-situ stresses, pore pressure, well bore pressure, and elastic rock properties).
3) Failure criterion (a rule that tells under what combinations of stresses the rock will fail).

2.2 Cause of Borehole Failure

Borehole instability occurs if the stress condition acting in the near-wellbore region exceeds the rock strength. Before a wellbore is drilled, the rock underground 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) [7]. When the well is drilled, the rock surrounding the borehole must support the load that was previously taken by the removed rock [4]. The rock stresses in the range of the wellbore will be redistributed. 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 [8, 9]. 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 2.

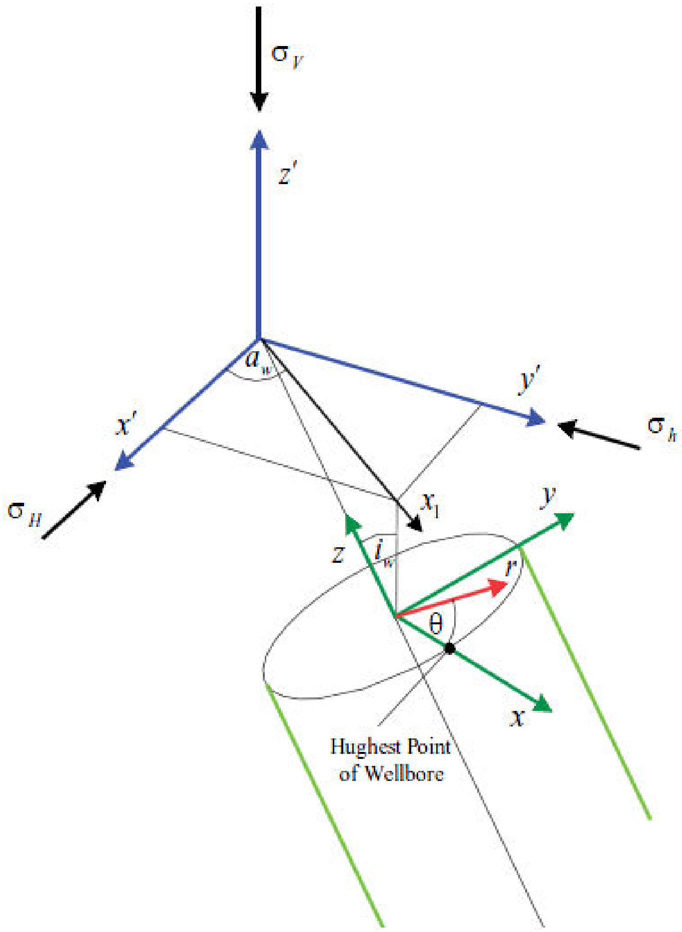

Figure 2.2: The coordinate system for the in-situ stress system [10]

2.3 Stress Distribution around the Borehole

The different axis definitions in different studies have introduced a lot of confusion as to how the borehole orientation is described. To terminate that confusion, a systematic, logical, and “right-handed” global coordinate system is defined for the in-situ stress condition and borehole orientation. Furthermore, a local coordinate system is used to describe the mechanical relationships in the plane perpendicular to the borehole axis.

Using linear elasticity theory, the stress distribution around the bore hole is described using the local cylindrical coordinate system (*r, θ, z*) [4]. The angular variation θ is measured anti-clockwise (right-hand rule) from the local X-axis towards the local Y-axis, while the local Z-axis is aligned with the borehole axis with increasing depth. The equations for the stresses will be limited to the plane-strain case, where no displacements along axis of the bore hole are assumed. The total stress distribution around the borehole equations can be elaborated using the formulas by Kirsch's solution [4] and assuming plane-strain conditions:

$$\sigma_{rr} = \frac{1}{2}\left(1 - \mathrm{r}_\mathrm{r}^2\right)(\sigma_\mathrm{x} + \sigma_y) + \frac{1}{2}\left(1 - 4\mathrm{r}_\mathrm{r}^2 + 3\mathrm{r}_\mathrm{r}^4\right)(\sigma_\mathrm{x} - \sigma_y)\cos 2\theta + \left(1 - 4\mathrm{r}_\mathrm{r}^2 + 3\mathrm{r}_\mathrm{r}^4\right)\sigma_{\overline{\mathrm{xy}}}\sin 2\theta + \mathrm{r}_\mathrm{r}^2\mathrm{P}_\mathrm{w} \quad \text{.............................. (2.1)}$$

$$\sigma_{\theta\theta} = \frac{1}{2}\left(1 + \mathrm{r}_\mathrm{r}^2\right)(\sigma_\mathrm{x} + \sigma_y) - \frac{1}{2}\left(1 + 3\mathrm{r}_\mathrm{r}^4\right)(\sigma_\mathrm{x} - \sigma_y)\cos 2\theta - \left(1 + 3\mathrm{r}_\mathrm{r}^4\right)\sigma_{\overline{\mathrm{xy}}}\sin 2\theta - \mathrm{r}_\mathrm{r}^2\mathrm{P}_\mathrm{w} \quad \text{..(2.2)}$$

$$\sigma_{\mathrm{zz}} = \sigma_{\overline{\mathrm{zz}}} - 4\nu\,\mathrm{r}_\mathrm{r}^2\left(\frac{\sigma_x - \sigma_y}{2}\cos 2\theta + \sigma_{\overline{\mathrm{xy}}}\sin 2\theta\right) \quad \text{.. (2.3)}$$

$$\sigma_{\mathrm{r}\theta} = \left(1 - 3\mathrm{r}_\mathrm{r}^4 + 2\mathrm{r}_\mathrm{r}^2\right)\left(\frac{\sigma_x - \sigma_y}{2}\sin 2\theta + \sigma_{\overline{\mathrm{xy}}}\cos 2\theta\right) \quad \text{... (2.4)}$$

$$\sigma_{\mathrm{rz}} = \left(1 - \mathrm{r}_\mathrm{r}^2\right)(\sigma_{\overline{\mathrm{xz}}}\cos\theta + \sigma_{\overline{\mathrm{yz}}}\sin\theta) \quad \text{.. (2.5)}$$

$$\sigma_{\theta z} = \left(1 + \mathrm{r}_\mathrm{r}^2\right)(-\sigma_{\overline{\mathrm{xz}}}\sin\theta + \sigma_{\overline{\mathrm{yz}}}\cos\theta) \quad \text{.. (2.6)}$$

Figure 2.3 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 [10].

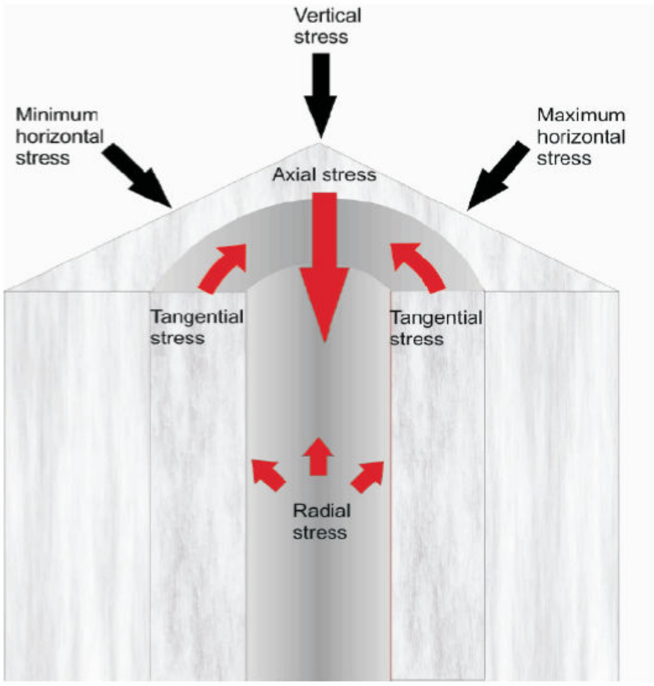

Figure 2.3: Stresses around wellbore [10]

Local stresses induced by in-situ stress and hydraulic effects at the wellbore wall ($r = r_w$), for <u>vertical well</u> can be described as follows [10]:

$$\sigma_r = P_w \quad \text{.......(2.7)}$$

$$\sigma_t = (\sigma_x + \sigma_y) - (\sigma_x - \sigma_h) \cdot \cos 2\theta - P_w \quad \text{.......(2.8)}$$

$$\sigma_a = \sigma_z - 2(\sigma_x - \sigma_y) \cdot v \cdot \cos 2\theta \quad \text{.......(2.9)}$$

According to the above equations, it can be concluded that the radial stress σ_r depends on the wellbore pressure (P_w) or mud weight [10]. The tangential stress, σ_t, depends on σ_h, P_w and θ. The wellbore stresses will diminish from the borehole wall and converting to far field stresses because away from the wellbore, the rock is in an undisturbed state [10]. Local stresses induced by in-situ stress and hydraulic effects at the wellbore wall ($r = r_W$), for deviated and horizontal wells can be expressed by [10]:

$$\sigma_r = P_w \quad (2.10)$$

$$\sigma_t = (\sigma_x + \sigma_y) - 2(\sigma_x - \sigma_y) \cdot \cos 2\theta - 4\tau_{xy} \cdot \sin 2\theta - P_w \quad (2.11)$$

$$\sigma_a = \sigma_z - v[2 \cdot (\sigma_x - \sigma_y) \cdot \cos 2\theta + 4\tau_{xy} \cdot \sin 2\theta] \quad (2.12)$$

$$\tau_{\theta z} = 2(\tau_{yz} \cdot \cos\theta - \tau_{xz} \cdot \sin\theta) \quad (2.13)$$

$$\tau_{r\theta} = \tau_{zz} = 0 \quad (2.14)$$

$$r_r = \frac{r_w}{r} \quad (2.15)$$

* r_r is the ratio of the actual radial position over the bore hole radius

Besides the in-situ stresses discussed above, an additional formation stress must be considered, namely, the pore pressure (P_p). Pore pressure is the pressure of fluids within the pores of the formation. It exists in all rocks but it can only be directly measured in sufficiently permeable rocks using RFT or MDT wire line tools [21]. Another approach is to deduce pore pressure from wireline or MWD logs (sonic, density or resistivity) [21]. For normally pressured formations, the pore pressure gradient is constant at approximately 0.465 psi/ft (10.5 kPa/m). For well compacted and cemented formation, the overburden stress varies linearly with depth, with a gradient approximately equal to 1.0 psi/ft (22.62 kPa/m) [4]. These values will be assumed as default value for P_p and σ_V throughout this report unless stated otherwise.

The total vertical in-situ stress can be obtained through integrating the density log. Meanwhile, the minimum horizontal in-situ stress (σ_h) can best be obtained through a Leak-Off Test (LOT) or preferably an extended Leak-Off Test (XLOT) or mini-frac test. In the petroleum industry, micro- and mini-frac tests are generally regarded as the best methods of estimating the minimum horizontal stress magnitude [22]. However, there is no direct measurement technique for measuring the maximum horizontal in-situ stress (σ_H). Possibly the best available method for estimating the magnitude of σ_H is to back-calculate its value from a micro- or mini-frac test that was run in an uncased borehole in competent rock [22].

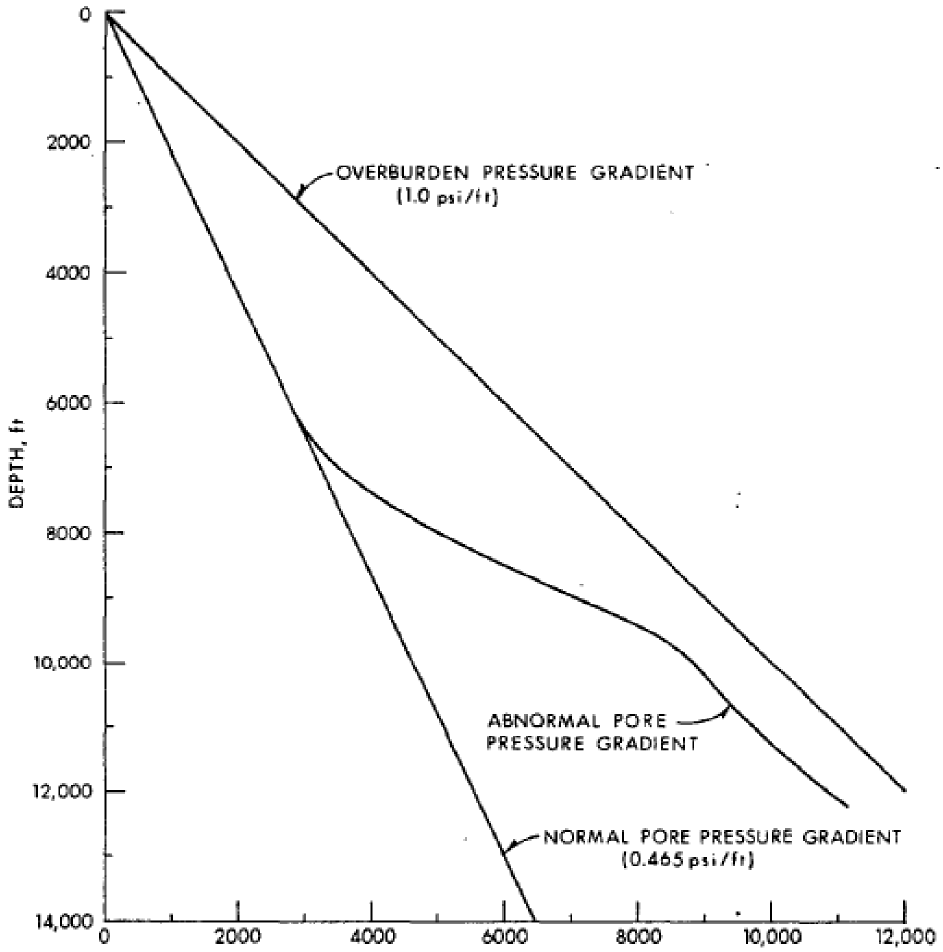

Figure 2.4: Estimated formations pressure gradient [4]

To evaluate failure of the rock matrix, effective stress is calculated. Effective stress is obtained by subtracting the pore pressure P_p from the normal stress components [17]. Normal stress components are calculated by multiplying the stress gradient with the true vertical depth.

$$\sigma'_v = \sigma_v - P_p \quad (2.16)$$

$$\sigma'_H = \sigma_H - P_p \quad (2.17)$$

$$\sigma'_h = \sigma_h - P_p \quad (2.18)$$

2.4 Rock Failure Criterion

Borehole fails if the in-situ stress either exceeding the tensile strength of the rock or exceeding the compressive strength of the rock [4, 11]. As the pressure in the well bore is increased, the stresses in the rocks become tensile. This will resulting in fracturing of the rock and lost circulation problems. With insufficient well bore pressure, the compressive strength of the rock is exceeded and the rock fails in compression. If the rock is in a brittle state, compressive failure produces rubble of the rock that fall into the hole, resulting in hole enlargement [4]. In other case, rocks which behave plastically under compressive loading will flow into the hole, resulting in a tight hole. Since the maximum stress state always occurs at the wall of the well bore, failure will always be initiated at the wall.

Compressive strength of rocks is usually determined by axially loading (σ_V) cylinders of rock to failure under several different confining pressures (σ_H, σ_h). In 1776, Coulomb introduced the simplest and most important failure criterion. He suggested that for rock in compression, failure takes place when the shear stress, τ developed on a specific plane reaches a value that is sufficient to overcome both the natural cohesion of the rock plus the frictional force that opposes motion along the failure plane [13]. This relation is expressed as:

$$\tau = \sigma_n \tan(\phi) + c \qquad (2.19)$$

where σ_n is the normal stress acting on the failure plane, c is the cohesion of the material and ϕ is the angle of internal friction.

When the stress at a point (represented by a Mohr circle plotted on a shear stress-normal stress plane) is great enough that the circle touches or crosses the failure envelope, failure will result [4]. Therefore, all states of stress lying to the right and below the failure envelope will be stable and regions lying above and to the left of the failure envelope will be unstable. The Mohr–Coulomb failure criterion represents the linear envelope that is obtained from a plot of the shear strength of a material versus the applied normal stress. Mohr's Circle was one of the leading tools used to visualize relationships between normal and shear stresses, and to estimate the maximum stresses [29].

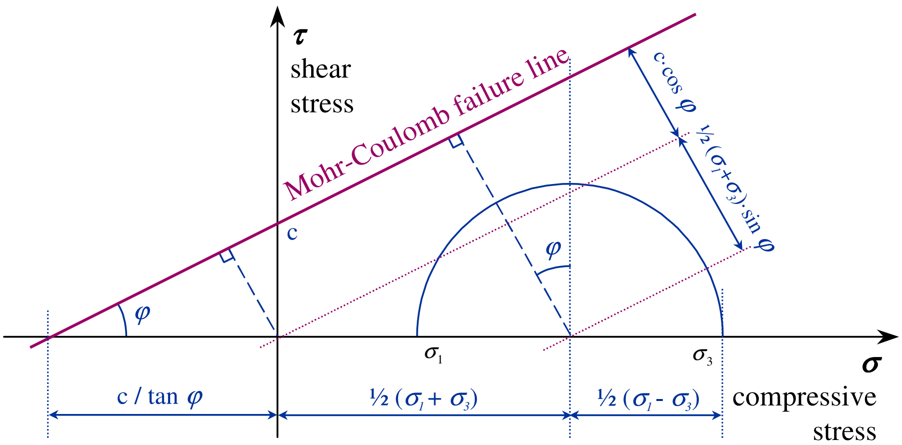

Figure 2.5: Mohr-Coulomb representation of failure - Mohr's Circle stress [28]

2.4.1 The Mohr-Coulomb shear failure criterion

The Mohr-Coulomb shear failure criterion evaluates the principal stress state against the failure condition, specified by the cohesion C and the friction angle ϕ, as outlined by the Mohr-circle diagram in Figure 2.5. Maximum shear stress of the rock is evaluated from Mohr's Circle:

Principal stresses:

$$\sigma_1 = \frac{\sigma_x + \sigma_y}{2} + \sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau_{xy}^{\ 2}} \quad \text{.........(2.20)}$$

$$\sigma_2 = \frac{\sigma_x + \sigma_y}{2} - \sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau_{xy}^{\ 2}} \quad \text{.........(2.21)}$$

Maximum shear stress:

$$\tau_{\max} = \frac{\sigma_1 - \sigma_2}{2} \quad \text{.........(2.22)}$$

From maximum shear stress, the maximum mud weight can be determined. The failure condition of a material point can be expressed by the Shear Capacity Utilisation (SCU) that relates the actual level of shear stress with the shear capacity of that point. Alternatively, this is also referred to as the τ/τ_{max} ratio or the Mohr-Coulomb failure ratio.

2.5 Mud Weight

Drilling mud plays important role in the successful completion of the drilling process. Mud serves various functions including exerting sufficient hydrostatic pressure against subsurface formations and preventing wellbore instability [19]. Selection of an appropriate mud weight is one way to prevent borehole failure. Mud pressure is the only parameter analysed routinely in a quantitative fashion, resulting in a recommendation for the mud weight margin (also referred to as drilling window) [12]. The mud-weight margin is the density range between pore and fracturing pressures. The mud weight or density is the main component. The mud or wellbore pressure (P_w) increases approximately proportional with depth (z) and is conveniently expressed as a pressure gradient (P_w/z).

2.5.1 Safe Mud Weight Margin

To determine safe mud weight margin, the minimum and maximum condition must be specified. The minimum safe mud pressure gradient is specified by the formation pore pressure gradient (P_p). The dynamic mud pressure gradient ($P_{w,\mathrm{d}}$) should exceed the pore pressure gradient in permeable intervals at all times to avoid influx of formations fluid. This is referred to as overbalance drilling [3]. The overbalance pressure can be seen as a support pressure for the rock matrix, and is a key element in stabilising the wellbore. The static mud weight required for well control is equal to the formation pressure plus a safe overbalance $\Delta P_{w,min}$ (200-400 psi) to account for pressure fluctuations [3]. The safe overbalance is assumed to be 200 psi (1.4 MPa) in this report unless stated otherwise. Equation 2.20 shows the minimum pressure condition.

$$P_w > P_p + \Delta P_{w,\,min}/z \quad \text{(2.23)}$$

Then, for the maximum safe mud pressure gradient, it should not exceed the minimum horizontal in-situ stress gradient (σ_h/z):

$$P_w < \sigma_h/z \quad \text{(2.24)}$$

Equations 2.20, 2.21 and 2.22 are used to define the margins of the safe, static and dynamic mud pressure gradients, as they are presented schematically in Figure 6.

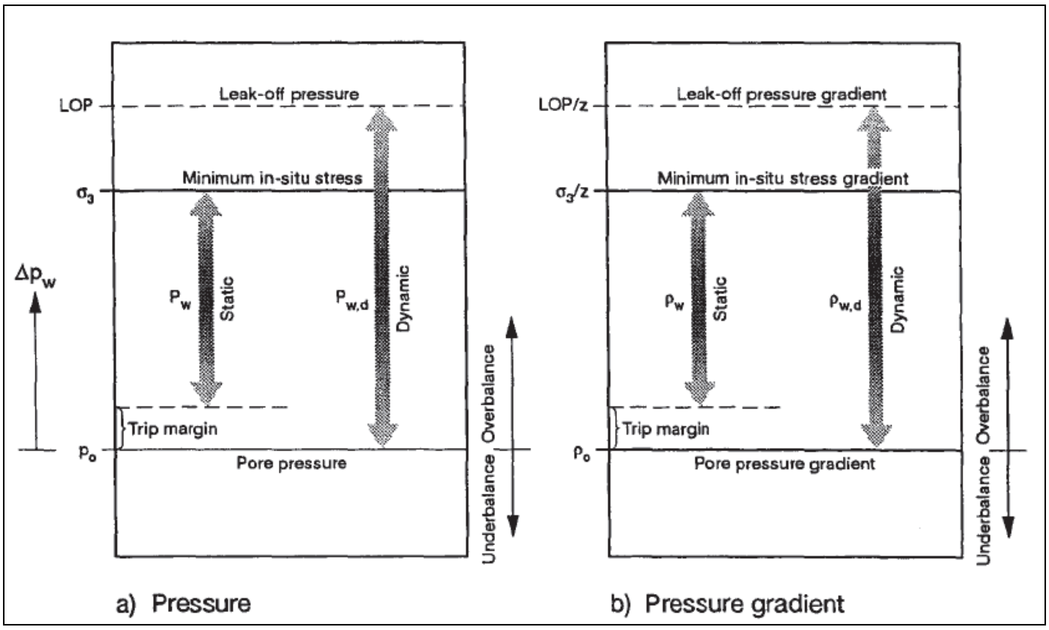

Figure 2.6: Safe margin for mud pressure (gradient) [3]

2.5.2 Elastic Mud Weight Margin

During drilling, mud absorbs pressure upon the wellbore wall and has a strong effect on the principal stresses acting upon the rock. If the mud pressure falls below a certain level, the wellbore will collapse due to lack of support from the mud column or formation fluid will enter the wellbore. In this situation, the wellbore may collapse in breakout or toric shear failure mode [19]. However, if the mud pressure exceeds a certain level, the wellbore will fail due to excessive mud pressures. Helical shear, elongated shear, or tensile failure may occur in this situation. Thus, it can be concluded that there will be two specific mud weights, one that describes a limiting value below which the wellbore will undergo failure, termed “lower bound” mud weight, and the other that describes the limiting value above which the wellbore will undergo failure, termed “upper bound” mud weight [19]. These limiting values are known as the elastic mud weight. If the mud weight is kept between the lower and upper bound, then the wellbore will be in a safe condition.

CHAPTER 3: METHODOLOGY

The work flow of this entire project can be described by flow chart below:

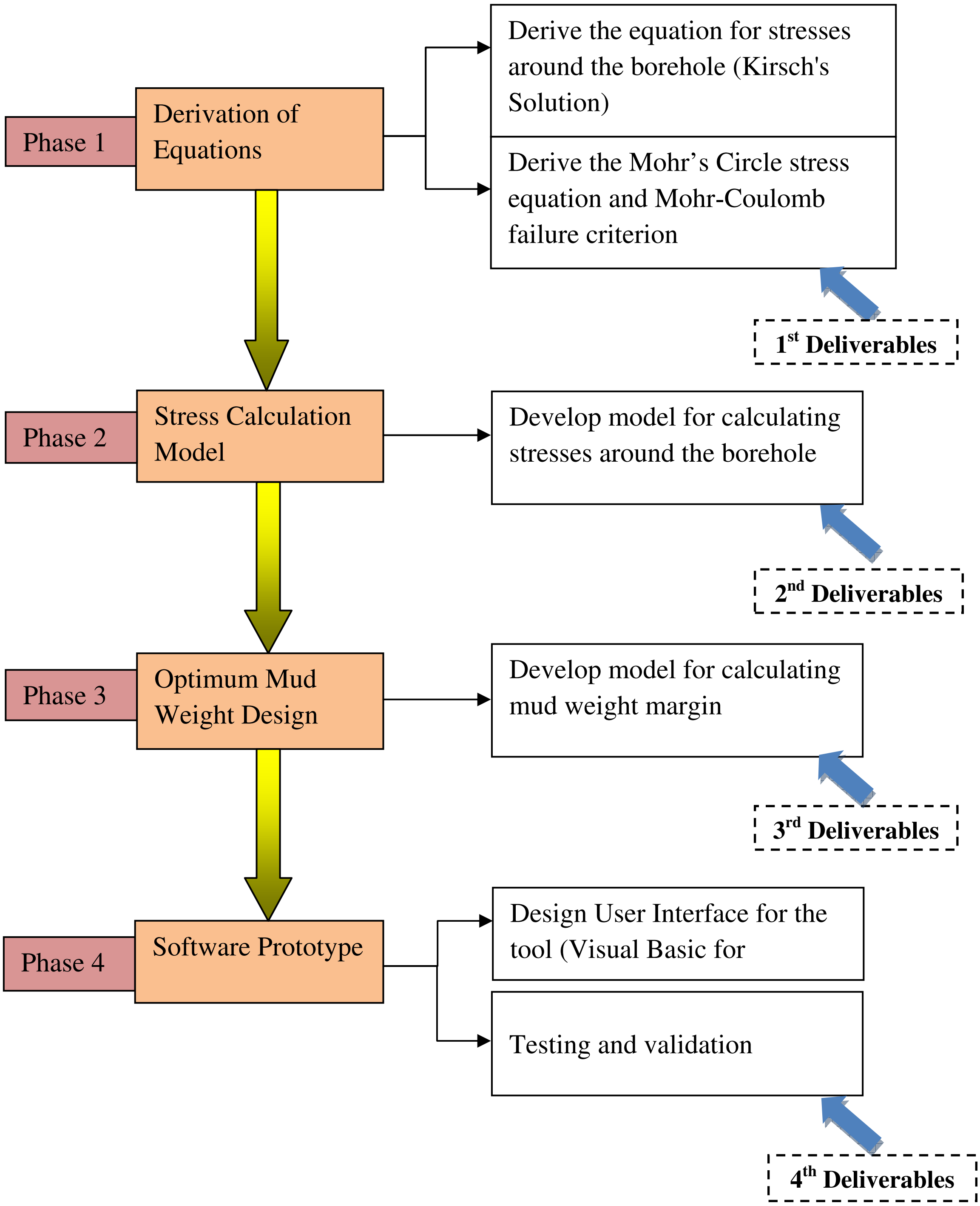

Figure 3.1: Project flow chart

Phase 1

It is known that borehole instability occurs if the stresses acting around the borehole exceed the rock strengths. Thus, the first step in understanding borehole instability is to solve and determine the governing equation to calculate the stresses around the borehole. The values of stresses acts around the borehole depend on four main parameters, which are the in-situ stress, pore pressure, inclination angle, and well azimuth. Based on these parameters, equations to calculate the effective stresses that acts around the borehole is developed.

After calculating the effective stresses around the borehole, the next step is to define the failure condition of the rock at that point. The tensile strength and tensile stress of the rock is estimated using the Mohr-Coulomb expression. The parameters required are rock cohesion, friction angle, and Poisson's Ratio. Using this relation, Mohr-Circle stress and Mohr-Coulomb line are plotted to estimate the failure condition.

Phase 2

At this stage, the governing equations for the stresses value and rock failure condition have been developed. The next step is to implement these governing equations into computer software. Microsoft Excel application is used as a platform to develop the software. This is because Microsoft Excel features calculation, graphing tools, pivot tables, and a macro programming language called Visual Basic for Applications which is suitable for this project. For the second phase, equations for stresses calculation are implemented into Microsoft Excel, followed by rock failure condition.

Phase 3

Drilling mud density plays an important role in balancing the borehole stability. The density of the mud that needs to be applied into the borehole is the focus of this project. Since the effective stresses around the borehole already can be determined, the project is continued by researching on the suitable mud weight margin. It is learnt that mud weight window is the density range between the pore and fracturing pressures. The mud weight must be able to withstand the formation pressure and in the same time not exceeding the formation strength. The equations to calculate the mud weight is developed and implemented into Microsoft Excel.

Phase 4

At this stage, all the calculations process required is already implemented into Microsoft Excel. The program can be used to calculate the stress distribution around borehole and also estimate the range of mud weight required. Also, there are several useful charts that had been plotted to provide the user with wider view of the borehole stability. However, it is not appropriate to be released as software since it is complex, not well organized and not user-friendly. So, the next step is to develop a Graphical User Interface (GUI) which acts as a medium of interaction for the user where they can key-in the required parameters and be presented with the desired result. This process is done by using Visual Basic for Applications (VBA).

To ensure the liability of the software, results validation is conducted. The mud weight range calculated is compared with the value produced in Shell SIEP report [24]. Also, the result is compared with earlier research that had already been conducted.

3.1 Calculation Method

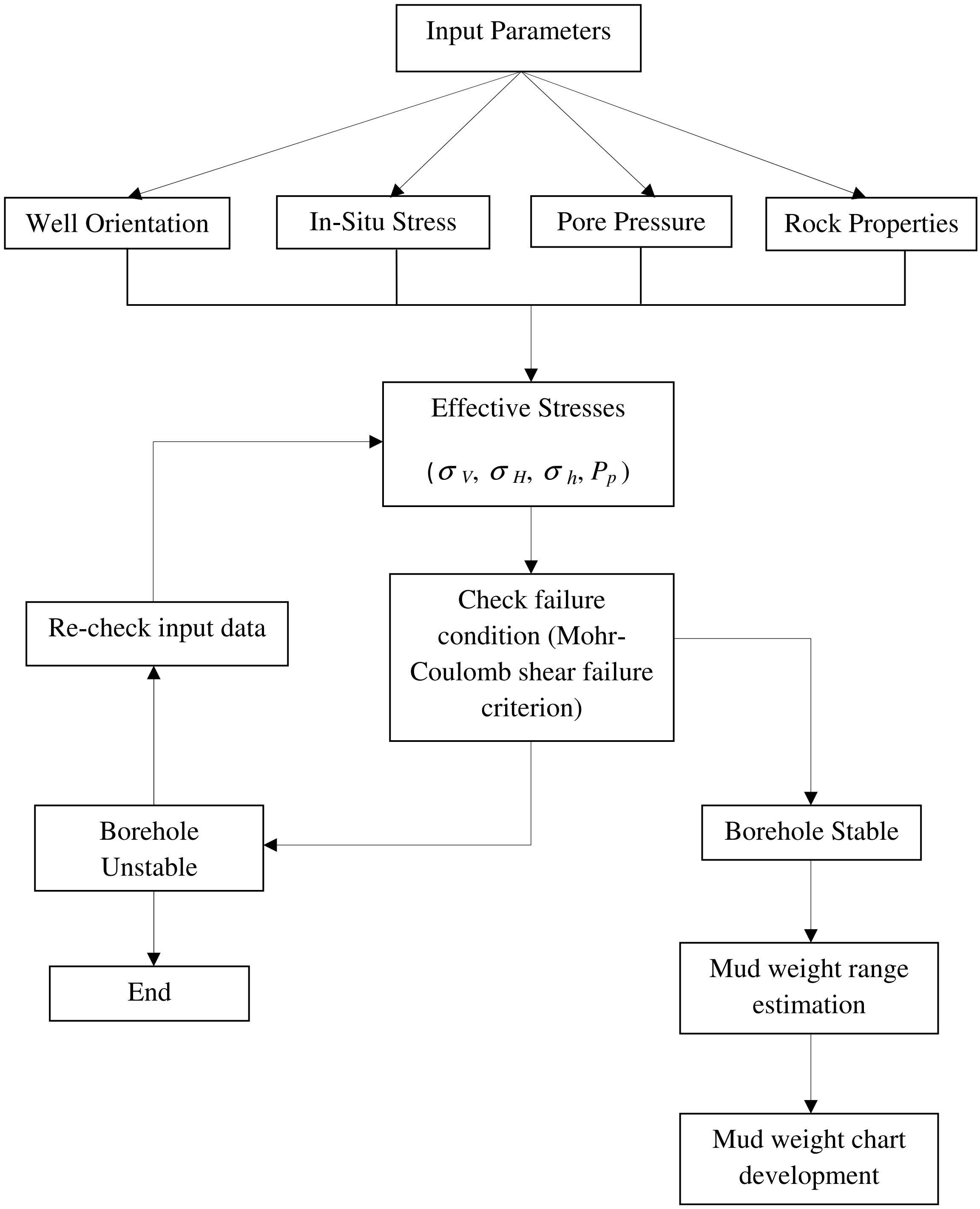

Figure 3.2: Flow chart for calculation method

There are 2 mathematical models involved in this project. The first one is model for effective stress calculation, and the other one is model for mud weight range prediction.

3.1.1 Effective Stresses

In order to calculate stress distribution around borehole and its failure limit, four main parameters are required, namely well orientation, in-situ stresses, pore pressure, and rock properties. From these parameters, effective stresses acting around the borehole is computed. The effective stress distribution around the borehole is relevant for evaluating failure of the rock matrix. To better understand how the parameters affect the result, a brief description for each parameters is given below:

<u>Well orientation</u>

Well orientation refers to the point where the stress will be calculated. It indicates the borehole position and direction. Well trajectory consists of true vertical depth, inclination angle, and well azimuth.

<u>In-situ stresses</u>

In-situ stress is the stress that acting at the point of interest, which consist of vertical stress, maximum horizontal in-situ stress, and minimum horizontal in-situ stress. In-situ stresses act around borehole and affecting its stability. Various sources can be used to estimate the in-situ stress condition. The total vertical in-situ stress is mostly obtained through integrating the density log. The density log for all major formation units from TVD up to surface are required for an accurate integration of the overburden weight.

<u>Pore pressure</u>

Pore pressure is required for effective stress calculation. Pore pressure tends to increase with depth according to the hydrostatic pressure gradient of 0.465 psi/ft (10.5 kPa/m).

Rock properties

Some rocks are able to withstand high pressure/stress. Meanwhile, there are also rock formations that are weak and porous. Therefore, rock properties are required to estimate the failure limit of the rock. Properties required are rock cohesion, friction angle, and its Poisson's Ratio.

3.1.2 Mud Weight Prediction

The critical mud weight to maintain borehole stability is calculated based on the elastic stress distribution around the bore hole as discussed earlier. This mud weight calculation model is developed based on Bradley's model (1979) which takes the formation to be linearly elastic and assume failure occurs when the peak strength of the rock is attained [23]. The algorithm is given to calculate the mud weight that causes the on-set of shear failure somewhere at the borehole wall. Thus, the so-called elastic-brittle mud weight is calculated assuming a Mohr-Coulomb shear failure criterion, as discussed in previous chapter (chapter 2.4.1). Similarly, the lost-circulation mud weight can be calculated. This mud weight causes the onset of tensile failure somewhere around the borehole wall.

The aim of this model is to calculate a static mud weight that should stabilise the borehole wall. That is, a fully drained formation is assumed. It is assumed that sufficient time has passed by to allow any change of pore pressure has dissipated. For favourable drilling conditions, a mud weight range should maintain the near-wellbore area in the elastic regime. The safe mud weight margin range is between the elastic-brittle mud weight and minimum horizontal in-situ stress gradient. Two failure phenomena determine the boundaries of the elastic window, which is shear failure and tensile failure. Shear failure usually results in collapse of the borehole material or breakout [18]. Meanwhile, the borehole tensile failure is defined by the minimum principal stress.

The mud weight that causes onset of shear failure in the high mud weight range is referred to as the Elastic Upper Limit. The Elastic-Brittle mud weight is a conservative estimation of the mud weight required to stabilise the bore hole. In any case, the Elastic-Brittle mud weight is the mud weight with the smallest over balance that keeps just two points at the borehole wall at the onset of shear failure [24]. The mud weight range between the Elastic-Brittle (EB) mud weight and the Elastic Upper Limit (UL) is called the “Elastic mud weight window”. It is noted; however, that an elastic mud weight window does not exists in all cases. Such situations imply highly unstable holes as no mud weight can prevent shear failure at the borehole wall.

The mud weight at the onset of tensile failure is referred to as Lost Circulation mud weight. Mud weight at Lost Circulation point, or higher than that, will cause the formation fracture which will create thief zone [24]. Lost circulation is associated with leak off of drilling fluids into fractures around the wellbore. Loss of drilling fluid will affect the drilling process which can lead to borehole failure. Also it increases the drilling cost. Thus, Lost Circulation point is marked as a limit to avoid the fracture of the formation and loss of drilling fluid.

The phenomenon of rock fracturing by spalling from the walls of boreholes is referred to as "borehole breakout" [26]. Results show that the initial breakout angle is the main factor that controls the breakout depth and the same initial breakout angle can be obtained from different stress-strength combinations so that there is a non-unique relationship between the in-situ stresses and the breakout shape and size. The initial breakout angle can be calculated directly from the Kirsch's solution for a given stress state [26]. The breakout angle is the angle subtended at the center of the borehole by the intersection of the breakout and the circumference of the borehole. The analysis of breakout formation by Gough and Bell [1981] and Bell and Gough [1982] predicted that breakouts are spalled regions on each side of the well bore which are centered at the azimuth of the least horizontal principal stress where the compressive stress concentration was greatest [27].

3.2 Gantt Chart and Milestone

3.2.1 Final Year Project 1

Detail/Week	1	2	3	4	5	6	7	Mid-Semester Break	8	9	10	11	12	13	14
Selection of Project Topic															
Preliminary Research Work Regarding Borehole Stability															
Literature Survey															
Working On Governing Equation For Stress Distribution Around Borehole															
Submission of Extended Proposal Defence															
Research On Stress Distribution Around Borehole Calculation Tool Using Microsoft Excel															
Determining Borehole Failure Criterion															
Proposal Defence Presentation															
Design User Interface (UI) For Stress Distribution Calculation Tool Using VBA															
Submission of Interim Draft Report.															
Submission of Interim Report.															

Table 3.1: Milestone and Gantt chart for FYP 1

3.2.2 Final Year Project 2

Detail/Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14	15
Project Work Continues								Mid-Semester Break								
Submission of Progress Report									●							
Project Work Continues																
Pre-EDX												●				
Interpretation and Validation Of The Result																
Submission of Draft Report													●			
Submission of Dissertation (Soft Bound)														●		
Submission of Technical Paper														●		
Oral Presentation															●	
Submission of Project Dissertation (Hard Bound)																●

Table 3.2: Milestone and Gantt chart for FYP 2

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Stress Analysis

For research and validation purpose, all the parameters' value for this project is taken from a SIEP Report done by Shell International Exploration and Production team [24].

Analysis point:	1	2	3	4	5	6
Stress Gradient / TVD	3688 m	3840 m	4054 m	4237 m	4389 m	5029 m
Vertical (kPa/m)	13.67	14.00	14.42	14.83	15.09	16.02
Maximum horizontal (kPa/m)	13.52	13.84	14.27	14.70	14.95	15.92
Minimum horizontal (kPa/m)	13.36	13.67	14.12	14.57	14.80	15.83
Pore pressure (max) (kPa/m)	12.00	12.95	13.59	13.59	13.64	13.42
Pore pressure (min)	11.89	12.26	12.42	12.46	12.57	13.42

Table 4.1: In-situ stress gradients in [kPa/m] at six key points along the well trajectory [24]

Property	Value	Unit
Young's modulus	0.646	[GPa]
Poisson's ratio	0.25	[-]
Cohesion	2.54	[MPa]
Friction angle	13.7	[deg]
Dilatancy angle	0.0	[deg]
Porosity	15.0	[%]
Permeability	10.0	[nD]
Fluid viscosity (water)	1.0	[cP]
Well inclination angle	0 (assumption)	[deg]
Well azimuth	0 (assumption)	[deg]

Table 4.2: Drained formation properties and well direction [24]

Four important values are required for effective stresses calculation, which are total vertical stress, total maximum horizontal stress, total minimum horizontal stress, and total pore pressure. These values are obtained by multiplying the stress gradient with true vertical depth. From that, the effective vertical stress, maximum effective horizontal stress, and minimum effective horizontal stress are obtained by subtracting pore pressure from each respective value. The result of total and effective stress calculation at point 1 (at 3688 m depth) is shown in table below:

Stress Distribution

Total Vertical Stress	50.41	MPa
Total Max. Horizontal Stress	49.86	MPa
Total Min. Horizontal Stress	49.27	MPa
Total Pore Pressure	44.26	MPa
Effective Vertical Stress	6.16	MPa
Max. Effective Horizontal Stress	5.61	MPa
Min. Effective Horizontal Stress	5.02	MPa
Maximum In-Situ Stress	6.16	MPa
Minimum In-Situ Stress	5.02	MPa

Table 4.3: Stress calculation

4.2 Mud Weight Analysis

The mud weight window serves as a critical design factor for the design of both the well and drilling fluid system [25]. It defines the range between the minimum weight to avoid well collapse (compressive failure) and the maximum mud weight to avoid formation breakdown (tensile fracturing) [25]. Depending on the parameters involved and situation, mud weight window may be very narrow under certain conditions, where the risk of failure is bigger. The objective of a mud weight evaluation is to obtain a first order estimate of the mud weight required to stabilise the borehole based on linear-elasticity theory. The evaluation yields the mud weight gradients that induces onset of shear and tensile failure at the borehole wall. The evaluation also provides a good mechanical understanding of the stability conditions along the well trajectory, which is usually not obtained through more complex computer codes. The result of mud weight window for point 1 (at 3688 m depth) is shown in figure 4.1.

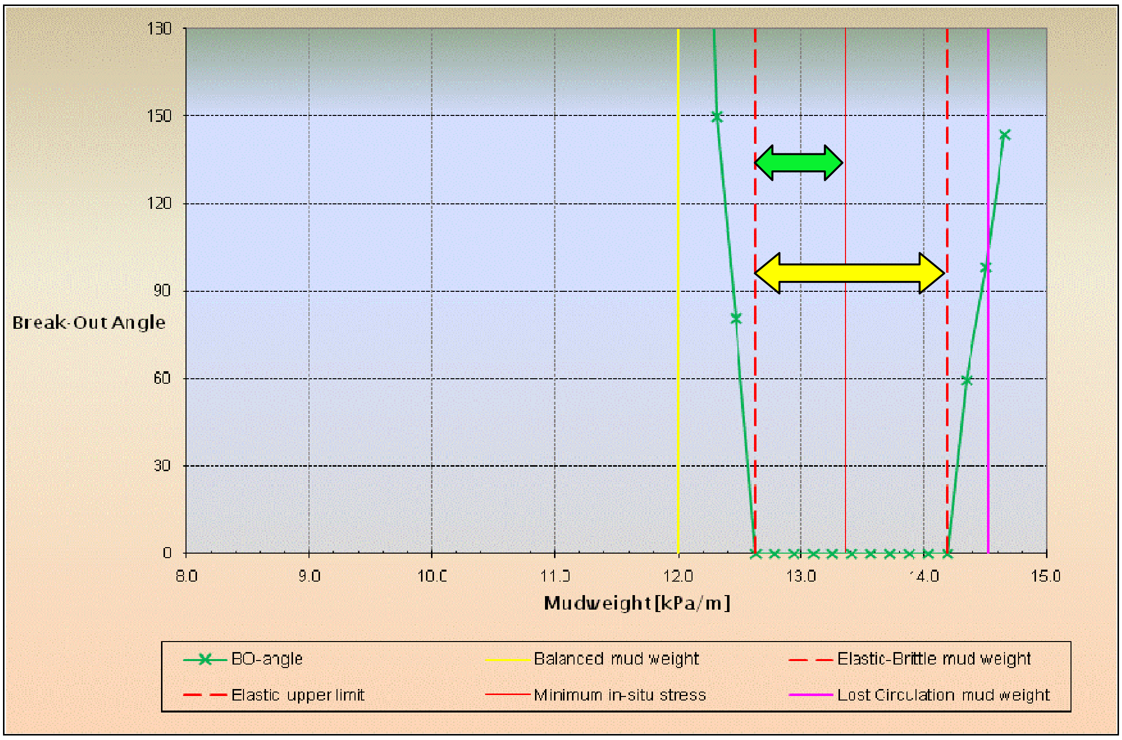

Figure 4.1: Mud weight window

The 'safe mud weight range' is shown by green arrow in Figure 6. This mud weight range is determined by taken into consideration the minimum horizontal in-situ stress. This is more conservative range where the maximum value is not exceeding the minimum horizontal in-situ stress gradient. However, this range is too narrow and not economically practical. Thus, by considering the rock tensile strength and rock properties, the 'elastic mud weight range' is calculated. The elastic mud weight range is shown by yellow arrow in Figure 6. The range between minimum and maximum value is where the breakout-angle is calculated to be zero (0), which indicated the wellbore is in stable condition.

Tensile stress and potential fracturing is initiated if the mud weight is raised too high in order to prevent instabilities due to shear failure. Fractures originating from the wellbore may lead to significant loss of drilling fluid. Based on previous reports and research, the mud weight that induces tensile failure is usually not equal to the minimum in-situ stress, because of the stress redistribution around the wellbore. This implies that the mud weight to initiate a fracture from the bore hole wall is different (oftenly higher) from the mud weight required to propagate the fracture beyond the zone of stress redistribution. Therefore, elastic mud weight margin approach is more practical in estimating the required mud weight.

4.3 Result Validation

The values of mud weight calculated in this project are compared with the result achieved from the Shell SIEP Report for a case study done in Netherlands. After comparison, the calculated mud weights range are close to the known mud weights in the case study used (shown in Figure 4.2).

Figure 4.2: Mud weight range comparison. *Green line indicates the range of mud weight calculated. Meanwhile, the red line indicates the results taken from Shell SIEP report.

There is slight difference in mud weight range for every point studied. The differences in mud weight calculated are because the well is assumed to be vertical in trajectory, since the exact coordinates of easting and northing for the well are not available. Also, several parameters at certain point need to be assumed due to limitation in field data. The variation in field data and method had produced variation in the results. However, the results obtained in this project are still within the range of mud weight estimated by Shell's research team. This shows that the techniques used for this project are correct and is applicable for industry scale. To study the effectiveness of the recommended mud weights further, the mud weight can be applied to the available database of oil wells.

4.4 Development of Mud Weight Chart

Mud weight chart is the range of mud weight estimated for along the well trajectory. This chart gives early evaluation of the mud weight range for along the well path. It allows the drilling engineers to plan ahead the development of the well and predict the wellbore stability and reliability. Mud weight chart can be developed for known well and also blind test well location. Figure 4.3 shows the result of mud weight chart developed for case study used.

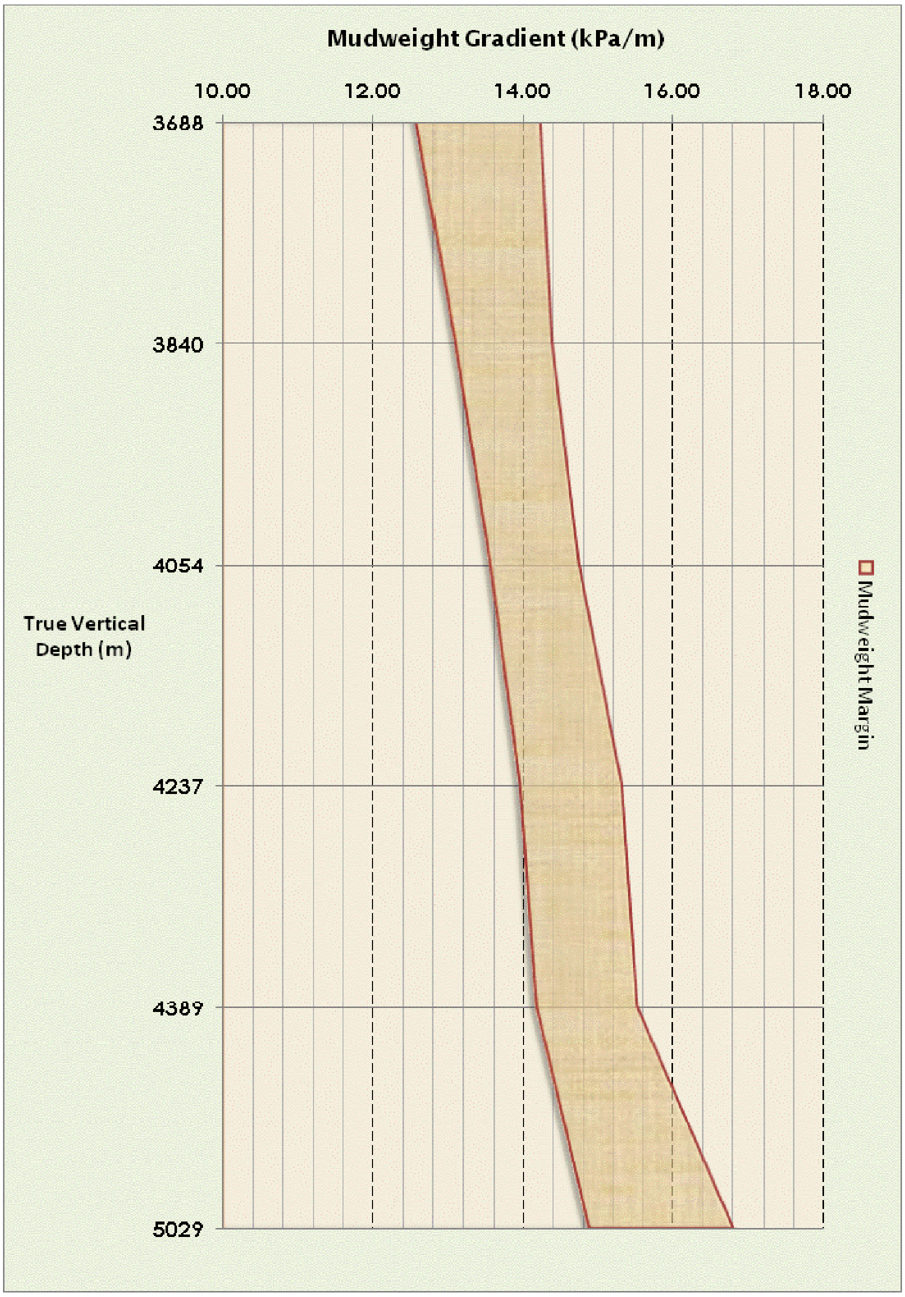

Figure 4.3: Mud weight chart developed for case study used

4.5 Prototype

In this project, software to predict borehole stability and mud weight margin is developed. The software prototype is developed by using Microsoft Excel VBA (Visual Basic for Application). All related equations are transferred into computer, through Microsoft Excel, and the Graphical User Interface (GUI) is done by using VBA. VBA coding is used to automate the calculation, provide loop for data calculation, and interact with user. From the GUI, user of the software will be prompted to fill in the basic parameter for stress and mud-weight calculation. After that, the input data will be calculated to generate the borehole failure analysis and also suitable mud-weight margin. Below is the screenshot of the latest version of the software which has been named as MudWindow:

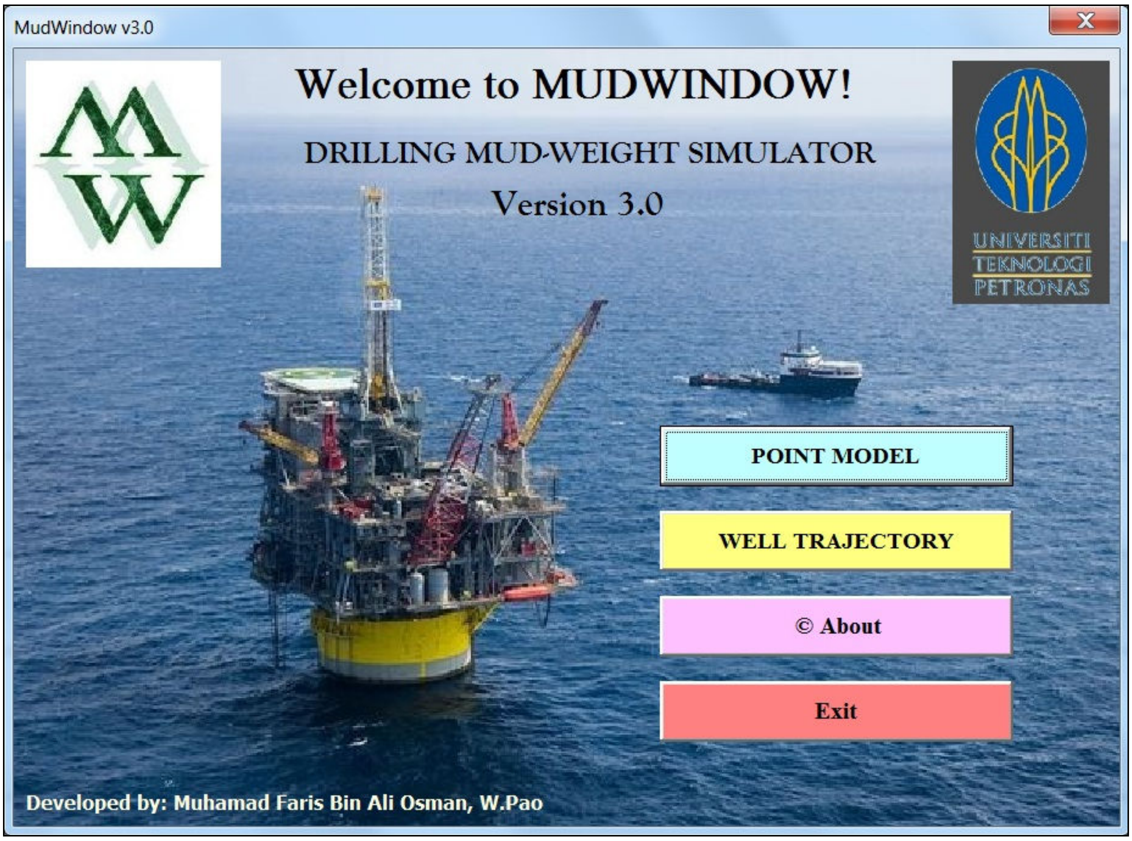

Figure 4.4: MudWindow Version 3.0 start-up page

At this start-up page, user can choose whether to use Point Model or Well Trajectory. Point Model is calculation done for single point-of-interest. Meanwhile, Well Trajectory option is for developing well trajectory and mud weight chart, which consist of several point-of-interests.

4.5.1 Point Model

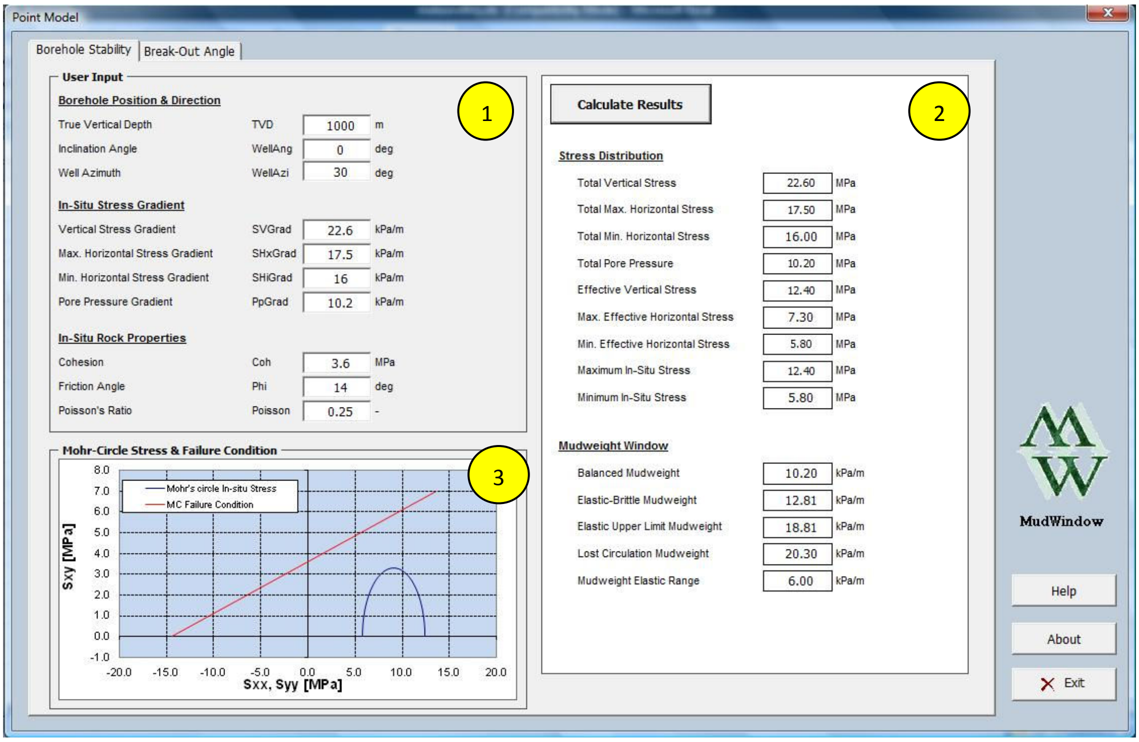

Figure 4.5: Borehole stability analysis

To use this software, the user will be prompted to fill in the parameters required at user input column (marked as section 1 in Figure 10). Then, the user can click the 'Calculate Result' button at section 2 where the results of effective stresses will be shown. Also, the estimated mud weight and its range will be calculated and displayed. At the same time, Mohr-Circle stress and failure condition will be plotted at section 3. This section allows the user to estimate the reliability and stability of the wellbore at that particular point. At the next tab, the corresponded mud weight range graph is displayed.

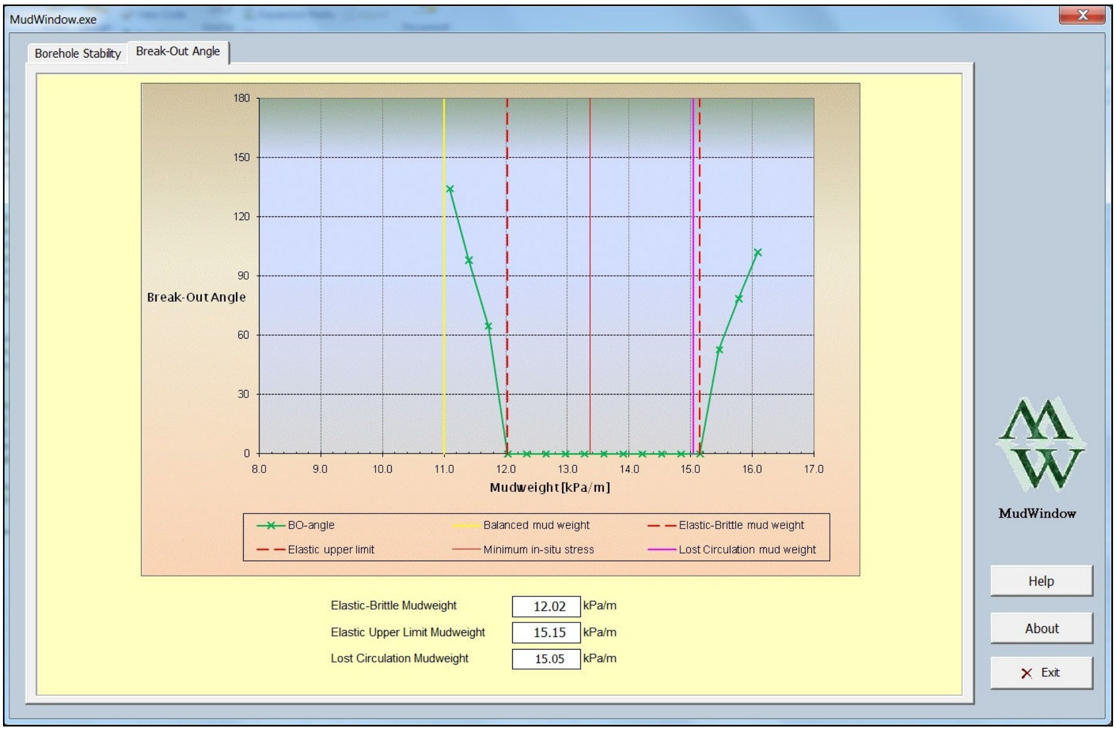

Figure 4.6: Mud weight Vs. Break-out angle graph

4.5.2 Well Trajectory

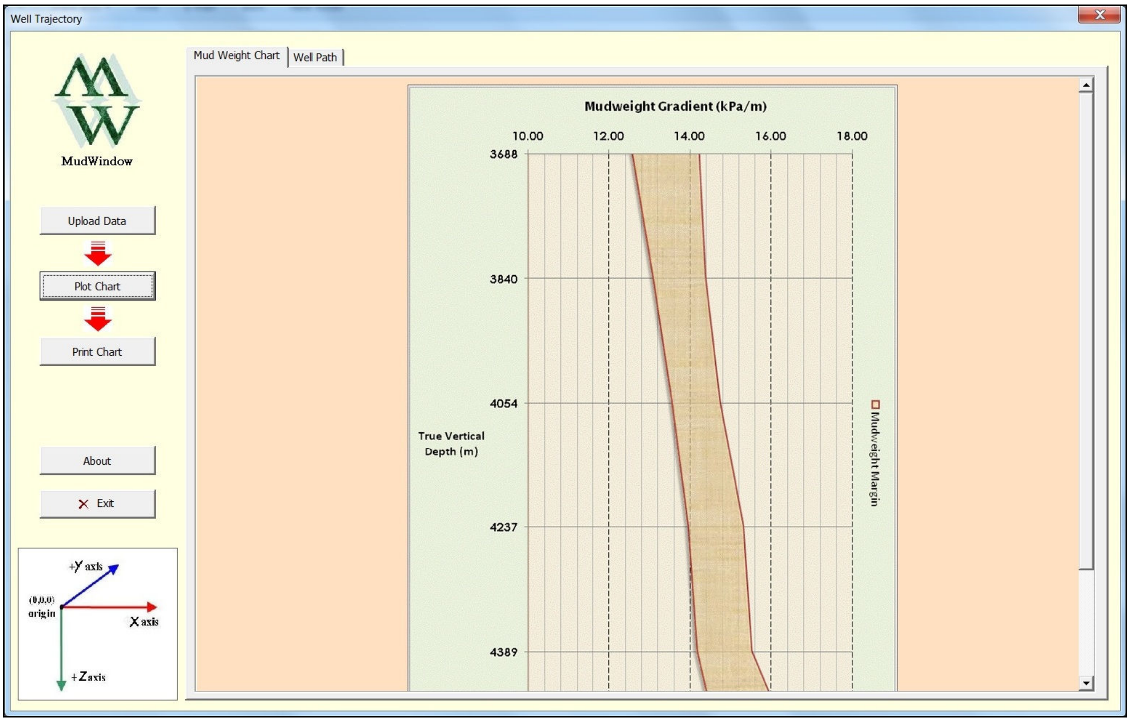

Figure 4.7: First section: Mud weight chart

At the first page of the Well Trajectory interface, the user will be asked to browse for their own data files where the coordinates of selected points-of-interest will be imported into the software. Then, the mud weight chart is plotted, where the user can see the mud weight range estimated for along the well path. On the next page, the well side view (as seen on X-axis and Y-axis) will be plotted. This section shows how the well trajectory behave from the start of drilling process until achieve the targeted point.

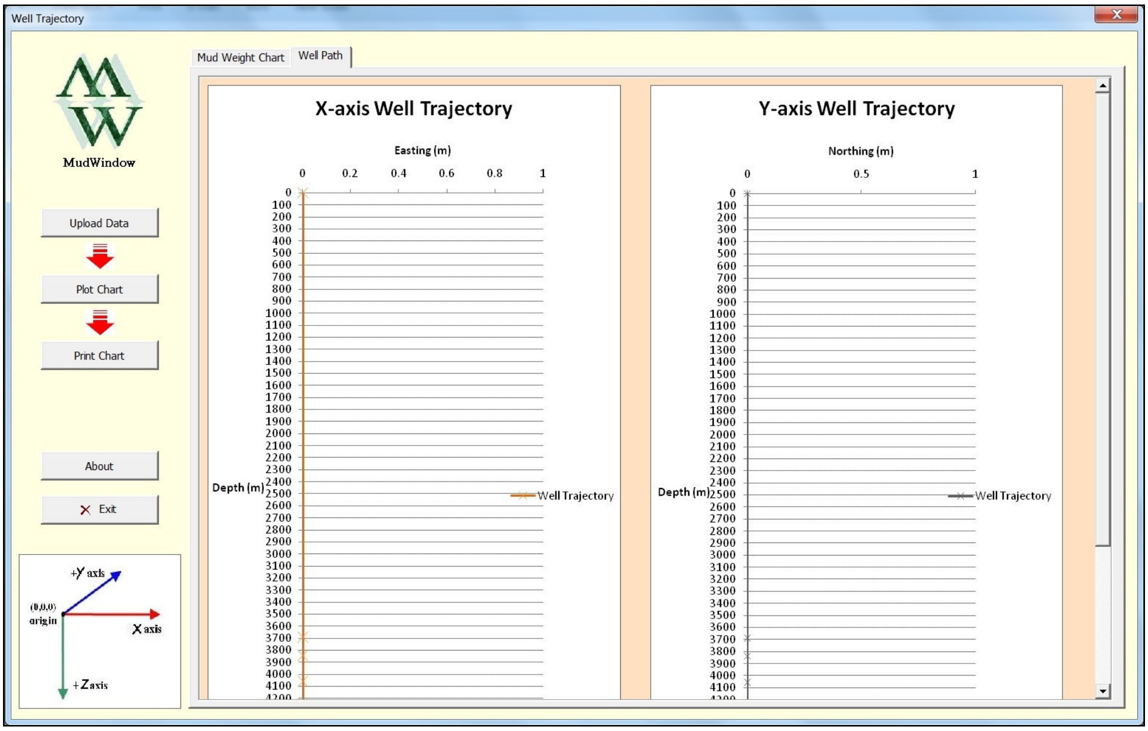

Figure 4.8: Second section: Side view of well path

CHAPTER 5: CONCLUSION AND RECOMMENDATION

5.1 Conclusion

Drilling mud purpose is to stabilize and balance the formation pressure. The suitable mud weight margin is important in avoiding borehole instability. The suitable mud weight margin should be able to withstand the stress distribution around borehole, and in the same time not fracturing the borehole wall. This narrow range of mud weight can be predicted through analysis of in-situ stress and rock compressive strength. Through this project, a simple mud weight prediction program has been successfully developed, which combining the stress distribution analysis and also rock failure criteria (Mohr-Coulomb shear failure criterion).

Results achieved shows that the linear-elasticity theory (finite element elasto-plastic model) can be implemented in predicting borehole stability. However, various failure criteria proposed in different literature can give major differences in predicted mud weight. Apart from that, it is observed that well trajectory influenced the mud weight margin required. The value of mud weight for inclined borehole is much higher than the value of mud weight for vertical well. Nevertheless, field data is very important in mud weight prediction. Detailed field data will allow more accurate prediction which can assure the stability and reliability of a borehole.

A software prototype has been successfully developed, which combines the basic theory in predicting borehole stability. Borehole stability prediction is vastly improved through the computer technology utilization. Besides the precise calculations, computer software allows more complex calculations to be implemented, which allow engineers to greatly reduce the possibility of failure in drilling process.

5.2 Recommendation

Borehole stability research required a lot of field data especially from geosciences related field. Results achieved can be improved and detailed calculation can be done if sufficient data are available. Therefore, students are encouraged to work closely with Geosciences Department and geologists for detailed and further references.

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APPENDICES

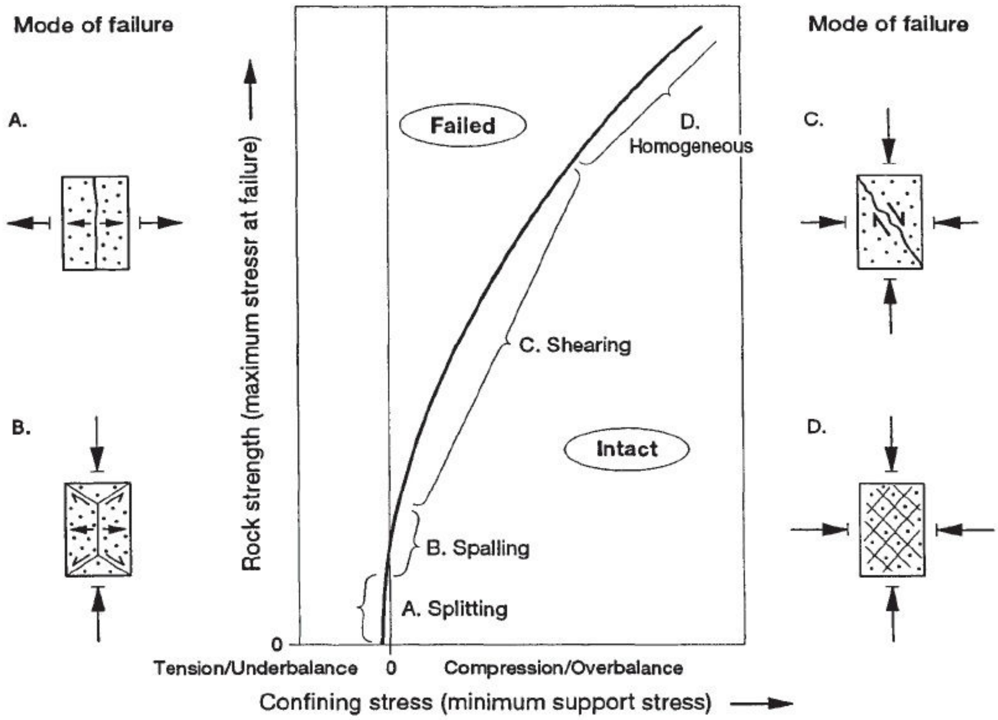

Figure (a): Rock strength and mode of failure as function of confining stress [3]

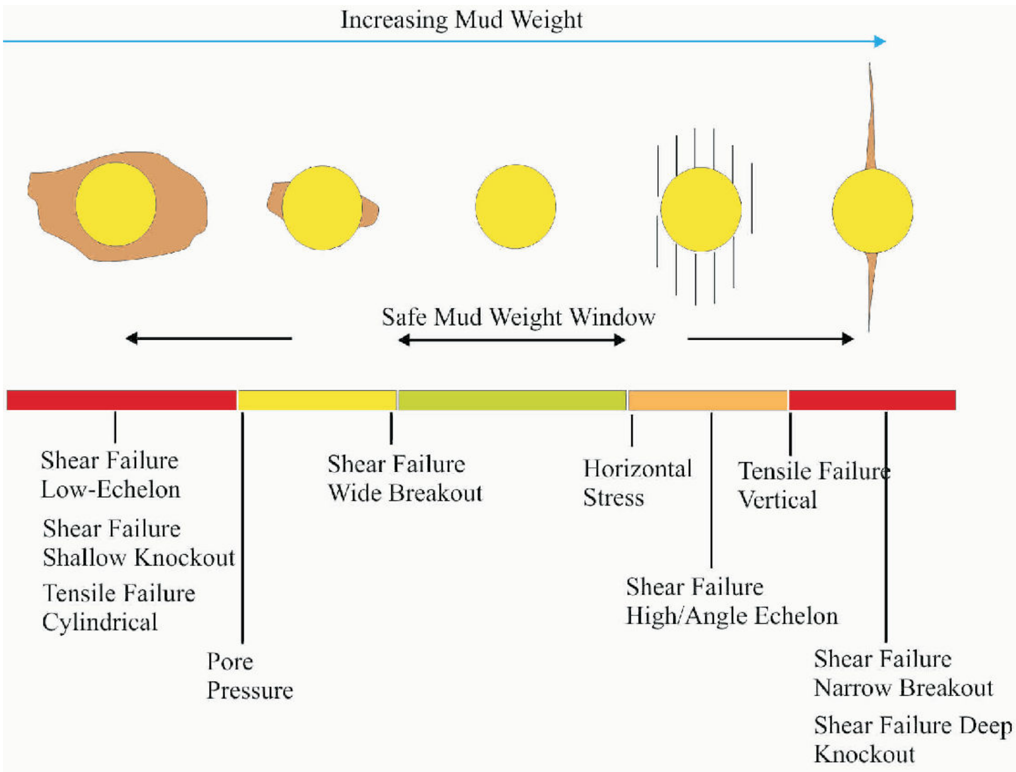

Figure (b): Effect of mud weight on the stress in borehole wall [10]

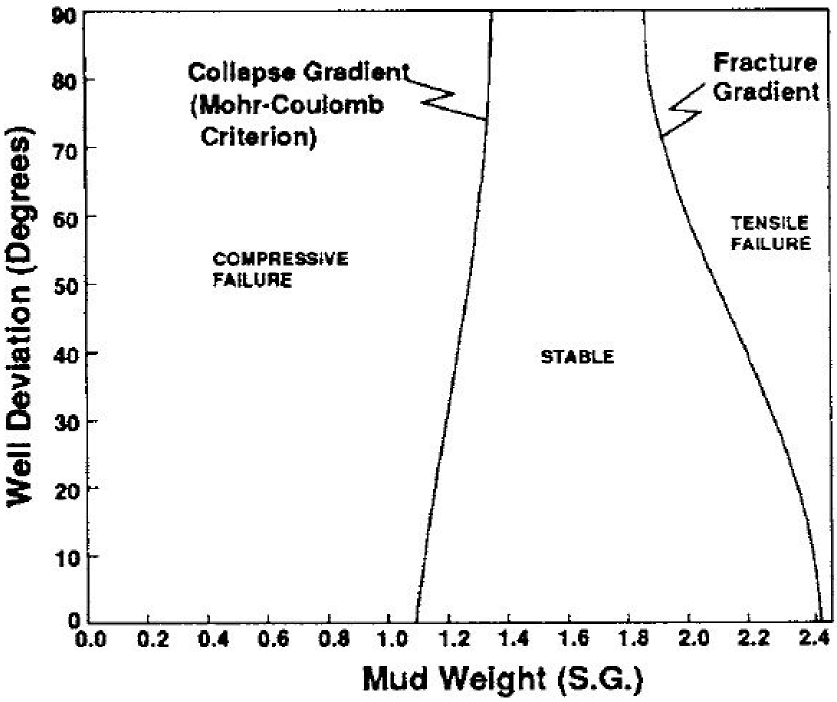

Figure (c): Range of safe mud weights assuming a Mohr-Coulomb criterion [9]

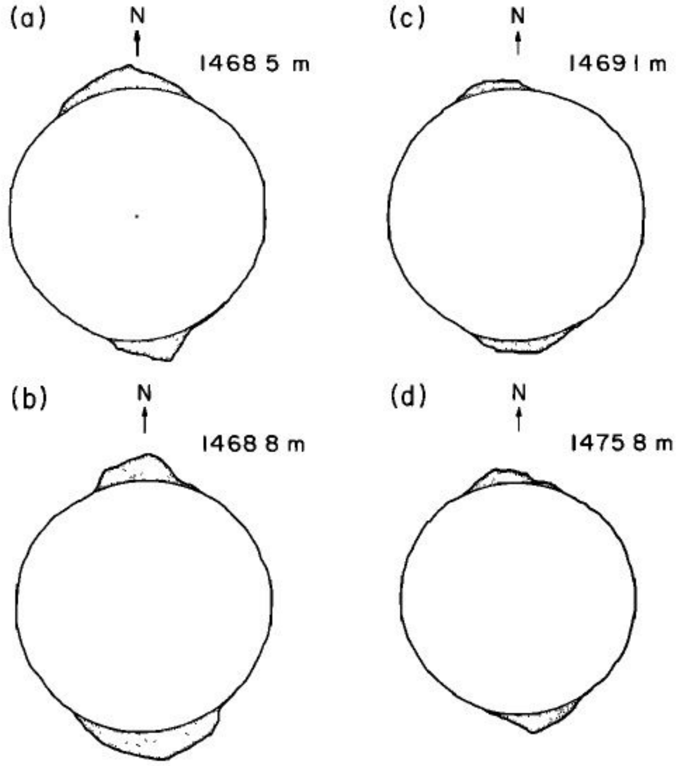

Figure (d): Representative breakout shapes in the Auburn, New York well [27]