AN APPROACH TO WELL BORE WALL STABILITY ANALYSIS BY
MATLAB AND FLAC3D SOFTWARE FOR SALMAN OIL FIELD

MAJID GHADERI

A thesis submitted in fulfillment of the
Requirements for the award of the degree of
Master of Science (Petroleum Engineering)

Faculty of Petroleum and Renewable Energy Engineering
Universiti Teknologi Malaysia

JUNE 2013
ACKNOWLEDGMENTS

I would like to express my sincere gratitude to my supervisor PM. Prof Mohd Nawy Derahman, for his support and encouragement throughout the duration of this work, I do admire his innovative approach and deep insight in scientific research, his ability to handle both research and consultancy work have motivated me in the present work and will inspire me in my academic career ahead.

I wish to acknowledge the affection of love of my family, my father, mother brother and especially my sister, who helped me from very first days of staying in Malaysia, whose constant inspiration was a great source of inspiration.

To My Lovely father and mother ...............
Abstract

Instability in wellbore wall is one of the most serious difficulties in drilling, because this problem can ultimately delay the drilling operations, increase cost of drilling and in some cases lead to the wellbore becoming abandoned. Now a day, with consideration of physical and chemical characteristics of mud we can apply the necessary changes to the composition of mud and make the wellbore wall more stable. With the help of the science of rock mechanics and the full knowledge of the characteristics of formation, the optimum path to drilling wellbore and the mud window can be calculated. In this research, first stability of the shale layer in wellbore 2SK5 in Salman oil field using analytical method (MATLAB software) and numerical method (FALC3D software) with the use of three criteria of failure of Mohr Coulomb, Mogi Coulomb and Drucker Prager will be studied and at the same time comparisons of applications of above criteria in stability of wellbore and comparisons of occurred difficulties in drilling this wellbore will be studied, and recommendations concerning drilling wellbore in the mentioned oil field will be presented, also at the same time some research work will be carried out in assessing drilling deviational wellbores in oil fields and effect of different stress regimes for calculating optimum direction and angle of deviation. Therefore, we conclude that stability of the wellbore with the increase in angle of deviation of wellbore does not necessarily decrease from that of its right angled one (90 degrees), unless in a case when stress is normal or the principal horizontal stresses are equal. Also, when stress regime is normal, drilling in the direction of minimum horizontal stress and decrease in angle of deviation of the wellbore from that of right angled one will be most stabilizing for the wellbore, but drilling in this direction in the other two stress regimes will result maximum instability.
Abstrak

Ketidakstabilan di dalam lubang telaga dinding adalah salah satu masalah yang paling serius dalam penggerudian, kerana masalah ini akhirnya boleh melambatkan operasi penggerudian, meningkatkan kos penggerudian dan dalam beberapa kes membawa kepada lubang telaga menjadi terbengkalai. Sekarang sehari, dengan mengambil kira ciri-ciri fizikal dan kimia lumpur, kita boleh memohon perubahan yang perlu untuk komposisi lumpur dan membuat dinding lubang telaga yang lebih stabil. Dengan bantuan sains mekanik batu dan pengetahuan yang penuh dengan ciri-ciri pembentukan, jalan yang optimum untuk penggerudian telaga dan tingkap lumpur boleh dikira. Kaedah analisis kerana simplicities mereka dan keperluan yang tidak perlu mereka untuk banyak ciri-ciri yang berkaitan dengan persekitaran lubang telaga yang boleh diketahui pada awal projek adalah agak berkenaan. Dalam kajian ini, kestabilan pertama lapisan syal dalam lubang telaga 2SK5 dalam bidang minyak Salman menggunakan kaedah analisis (MATLAB perisian) dan kaedah berangka (FALC3D software) dengan menggunakan tiga kriteria kegagalan Mohr Coulomb, Mogi Coulomb dan Drucker Prager akan dikaji dan pada masa yang sama perbandingan masa permohonan kriteria di atas dalam kestabilan lubang telaga dan perbandingan kesukaran berlaku dalam penggerudian telaga ini akan dikaji, dan pada masa yang sama perbandingan masa permohonan kriteria di atas dalam kestabilan lubang telaga dan perbandingan kesukaran berlaku dalam penggerudian telaga ini akan dikaji, dan cadangan mengenai telaga penggerudian di medan minyak tersebut akan dibentangkan, juga pada masa yang sama kerja-kerja penyelidikan yang akan dijalankan dalam menilai penggerudian wellbores deviational dalam bidang minyak dan kesan rejim tekanan yang berbeza untuk mengira arah optimum dan sudut sisihan.
1 INTRODUCTION
1.1 Research background 1
1.2 Statement of the problem 1
1.3 Objectives 2
1.4 Scopes 2

2 LITERATURE REVIEW
2.1 Introduction ........................................................................................................ 4
2.2 Stresses around the wellbore ........................................................................... 5
2.3 Calculating in situ stresses ............................................................................ 7
   2.3.1 Methods for specifying direction of in situ stresses ......................... 8
   2.3.2 Specifying in situ stresses ..................................................................... 8
2.4 Stresses in cylindrical coordination ............................................................... 10
2.5 Stresses around deviational wellbores ......................................................... 12
2.6 Specifying stresses around the wellbore wall ............................................. 16
   2.6.1 Wellbore wall stresses in elastic environment – Kirsch method 17
   2.6.2 Wellbore wall stresses in elastic plastic environments .............. 19
2.6.3 Deviational wellbores ................................................................. 21
2.6.4 Right angled wellbores ............................................................... 21
2.6.5 Horizontal wellbores ................................................................. 26
2.7 Calculating formation strength ......................................................... 28
2.8 Criteria of rock failure ................................................................. 29
  2.8.1 Strength and its basis ............................................................... 31
  2.8.2 Failure and intermediate principal stress .................................... 33
  2.8.3 Selecting a suitable criterion of failure ...................................... 36
  2.8.4 Shear failure ........................................................................... 39
  2.8.5 Tensile failure .......................................................................... 39
  2.8.6 Criteria of Coulomb ................................................................. 39
  2.8.7 Criteria of Mohr ....................................................................... 43
  2.8.8 Criteria of shear and tensile failure of Mohr Coulomb for vertical wellbore, homogeneous horizontal stresses and impermeable formations. (Shale) 44
  2.8.9 Criteria of Hook and Brown ..................................................... 46
  2.8.10 Criteria of Drucker Prager ....................................................... 47
  2.8.11 Criteria of Mogi .................................................................... 49
  2.8.12 Criteria of Mogi Coulomb ....................................................... 50
  2.8.13 Modified Lade failure criterion ............................................... 53
  2.8.14 Criteria of tensile failure ....................................................... 54

3 STEPS OF MODELING
3.1 Introduction .................................................................................. 55
3.2 Input parameters and flowchart for the analytical program ............... 56
3.3 Various numerical methods .......................................................... 57
  3.3.1 Finite element method ............................................................ 59
  3.3.2 Boundary element method ...................................................... 60
  3.3.3 Finite difference method ........................................................ 60
  3.3.4 Distinct element method ........................................................ 61
  3.3.5 Beam element with elastic support method ............................... 62
3.4 Getting to know the software

4 SALMAN OIL FIELD – ASSESSMENT OF WELLBORE STABILITY OF WELL 2SK5

4.1 Introduction

4.2 Technical specification of Salmon oil field and wellbore 2SK-5

4.3 Experimental results

4.4 Assessing instability with analytical method

4.5 Assessment of instability with numerical method

4.5.1 Problem modeling

4.6 Assessment of effects of different stress regimes at optimum azimuth and angle of deviation of wellbore in the Salmon oil field

4.6.1 Stress regimes

4.7 Assessment of different stress regimes

5 CONCLUSION
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>NO.FIGURE</th>
<th>TOPIC</th>
<th>PAGES</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>State of in situ stress around the wellbore</td>
<td>6</td>
</tr>
<tr>
<td>2.2</td>
<td>Transformation of Cartesian and Cylindrical coordination</td>
<td>10</td>
</tr>
<tr>
<td>2.3</td>
<td>System of in situ stresses of same coordination</td>
<td>13</td>
</tr>
<tr>
<td>2.4</td>
<td>System of transformation of stress for deviational wellbores</td>
<td>13</td>
</tr>
<tr>
<td>2-5</td>
<td>Position of the wellbore wall in situ stresses and their changes</td>
<td>17</td>
</tr>
<tr>
<td>2-6</td>
<td>Right angled wellbore in a heterogeneous formation with horizontal stress</td>
<td>23</td>
</tr>
<tr>
<td>2-7</td>
<td>Stresses around a wellbore in a homogeneous linear elastic formation.</td>
<td>24</td>
</tr>
<tr>
<td>2-8</td>
<td>System of transformation for right angled wellbore</td>
<td>24</td>
</tr>
<tr>
<td>2-9</td>
<td>Change in principal stress due to drilling a non heterogeneous wellbore</td>
<td>25</td>
</tr>
<tr>
<td>2-10</td>
<td>Change in tangential stress due to drilling a heterogeneous wellbore</td>
<td>26</td>
</tr>
<tr>
<td>2-11</td>
<td>System of transformation for horizontal wellbores</td>
<td>27</td>
</tr>
<tr>
<td>2-12</td>
<td>Horizontal wellbore in a formation with heterogeneous horizontal stresses</td>
<td>28</td>
</tr>
<tr>
<td>2-13</td>
<td>Shape of test sample in a uniaxial test</td>
<td>30</td>
</tr>
<tr>
<td>2-14</td>
<td>Diagram of principal stress changes in relation to change in shape</td>
<td>30</td>
</tr>
<tr>
<td>2-15</td>
<td>Effect of composite stresses on shape of the sample curves of triaxial stresses over strain</td>
<td>31</td>
</tr>
</tbody>
</table>
2-16 Varieties of failures in wellbore wall and its regions ......................... 37

2-17 (Swelling) in new and soft shale and wash out wall of wellbore in brittle formations ................................................................................................................. 38

2-18 Inductive fracture due to too much mud weight .................................. 38

2-19 A picture of wide wash out .................................................................. 38

2-20 Coulomb criteria of failure .................................................................... 41

2-21 Strength push under effect of principal stresses ................................... 41

2-22 Strength push under effect of Coulomb tensile force ........................... 42

2-23 Criteria of failure of Mohr Coulomb ..................................................... 43

2-24 Graph of different modes of different wellbore fracture ...................... 46

2-25 Rock push of Mogi Coulomb ................................................................. 52

2-26 Rock push of Mogi Coulomb with a tensile separated piece ............... 53

3-1 Flowchart for program of wellbore stability for the Criterion of Mogi Coulomb 57

3-2 Process of calculation used in explicit method for one step ..................... 64

4 Structural map of Salmon oil field with position of drilled wellbores in this field 67

4-1 Graph of density showing amount of formation density relative to depth in gr/cm3 68

4-2 Graph of pressurized sound ................................................................ 69

4-3 Graph of shear sound ........................................................................... 69
4-4 Graph of ratio of derived Poisson from graphs of shear, pressurized and density sound...............................................................70

4-5 Graph of derived over burden load pressure from log density........70

4-6 Graph of minimum horizontal stress derived from equation..........71

4-7 Graph of maximum horizontal stress derived from equation..........71

4-8 Graph of diameter of the wellbore over depth ...........................73

4-9 Graphs of lower limit of the window of mud based on Mohr Coulomb, Mogi Coulomb and Drucker Prager and its upper limit (tensile failure) at point 1 and applied pressure of mud in the wellbore with angle of deviation of 25.7 degrees75

4-10 Graph of lower and upper limits of the window of mud based on changes in azimuth at point 1 with the use of the criteria of failure of Mohr Coulomb 77

4-11 Graph of lower and upper limits of the window of mud based on changes in azimuth at point 1 with the use of the criteria of failure of Mogi Coulomb 77

4-12 Graph of lower and upper limits of the window of mud based on changes in azimuth at point 1 with the use of the criteria of failure of Drucker Prager 78

4-13 Three dimensional graphs of mud pressure, azimuth and angle of deviation at point 1 with the use of the criteria of failure of Mohr Coulomb .................78

4-14 Three dimensional graphs of mud pressure, azimuth and angle of deviation at point 1 with the use of the criteria of failure of Mogi Coulomb ...............79

4-15 Three dimensional graphs of mud pressure, azimuth and angle of deviation at point 1 with the use of the criteria of failure of Drucker Prager ...............79

4-16 Lower limit of the window of mud based on the criteria of Mohr Coulomb, Mogi Coulomb and Drucker Prager and its upper limit (tensile failure) at point 2 and applied mud pressure in the wellbore with angle of deviation of 25.7 degrees ....81
4-17  Graph of lower and upper limit of the window of mud based on changes of azimuth at point 2 with the use of the criteria of failure of Mohr Coulomb ......  82

4-18  Graph of lower and upper limit of the window of mud based on changes of azimuth at point 2 with the use of the criteria of failure of Mogi Coulomb ......  82

4-19  Graph of lower and upper limit of the window of mud based on changes of azimuth at point 2 with the use of the criteria of failure of Drucker Prager ......  83

4-20  Three dimensional graphs of mud pressure, azimuth and angle of deviation at point 2 with the use of the criteria of failure of Mohr Coulomb .......................  84

4-21  Three dimensional graphs of mud pressure, azimuth and angle of deviation at point 2 with the use of the criteria of failure of Mogi Coulomb .......................  84

4-22  Three dimensional graphs of mud pressure, azimuth and angle of deviation at point 2 with the use of the criteria of failure of Drucker Prager .......................  85

4-23  Lower limit of the mud window based on the criteria of Mohr Coulomb, Mogi Coulomb and Drucker Prager and its upper limit (tensile stress) at point 3 and applied mud pressure in the wellbore with angle of deviation of 25.7 degrees ...............  86

4-24  Graph of lower and upper limits based on changes of azimuth at point 3 with the use of the criteria of failure of Mohr Coulomb........................................  87

4-25  Graph of lower and upper limits based on changes of azimuth at point 3 with the use of the criteria of failure of Mogi Coulomb........................................  87

4-26  Graph of lower and upper limits based on changes of azimuth at point 3 with the use of the criteria of failure of Drucker Prager ........................................  88

4-27  Three dimensional graphs of mud pressure, azimuth and angle of deviation at point 3 with the use of the criteria of failure of Mohr Coulomb .................  89

4-28  Three dimensional graphs of mud pressure, azimuth and angle of deviation at point 3 with the use of the criteria of failure of Mogi Coulomb .................  89
<table>
<thead>
<tr>
<th>Page</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>4-29</td>
<td>Three dimensional graphs of mud pressure, azimuth and angle of deviation at point 3 with use of the criteria of failure of Drucker Prager</td>
</tr>
<tr>
<td>4-30</td>
<td>Sound and density logs</td>
</tr>
<tr>
<td>4-31</td>
<td>Model made with the use of FALC3D</td>
</tr>
<tr>
<td>4-32</td>
<td>Counters of movements after becoming stable in relation to first point</td>
</tr>
<tr>
<td>4-33</td>
<td>Vectors of movements after becoming stable in relation to first point</td>
</tr>
<tr>
<td>4-34</td>
<td>Lower limit of the window of mud based on the criteria of failure of Mohr Coulomb, Mogi Coulomb and Drucker Prager at point 1 and applied mud pressure in the wellbore with angle of deviation of 25.7 degrees</td>
</tr>
<tr>
<td>4-35</td>
<td>Lower limit of the window of mud based on the criteria of failure of Mohr Coulomb, Mogi Coulomb and Drucker Prager at point 2 and applied mud pressure in the wellbore with angle of deviation of 25.7 degrees</td>
</tr>
<tr>
<td>4-36</td>
<td>Lower limit of the window of mud based on the criteria of failure of Mohr Coulomb, Mogi Coulomb and Drucker Prager at point 3 and applied mud pressure in the wellbore with the angle of deviation of 25.7 degrees</td>
</tr>
<tr>
<td>4-37</td>
<td>Types of stress regimes</td>
</tr>
<tr>
<td>4-38</td>
<td>Changes in graph of mud pressure in relation to change of azimuth with different angle of deviation of the wellbore in first stress regime</td>
</tr>
<tr>
<td>4-39</td>
<td>Changes of graph of 3 dimensional mud pressure in relation to change of azimuth with different angle of deviation of wellbore in 2nd stress regime</td>
</tr>
<tr>
<td>4-40</td>
<td>Changes in graph of mud pressure in relation to change of azimuth with different angle of deviation of the wellbore in 2nd stress regime</td>
</tr>
<tr>
<td>4-41</td>
<td>Changes of graph of 3 dimensional mud pressure in relation to change of azimuth with different angle of deviation of wellbore in 3rd stress regime</td>
</tr>
</tbody>
</table>
4-42 Changes in graph of mud pressure in relation to change of azimuth with different angle of deviation of the wellbore in 3\textsuperscript{rd} stress regime ............................................. 104

4-43 Changes of graph of 3 dimensional mud pressure in relation to change of azimuth with different angle of deviation of wellbore in 4\textsuperscript{th} stress regime ...... 105

4-44 Changes in graph of mud pressure in relation to change of azimuth with different angle of deviation of the wellbore in 4\textsuperscript{th} stress regime ............................................. 105

4-45 Changes of graph of 3 dimensional mud pressure in relation to change of azimuth with different angle of deviation of wellbore in 5\textsuperscript{th} stress regime ...................... 106

4-46 Changes in graph of mud pressure in relation to change of azimuth with different angle of deviation of the wellbore in 5\textsuperscript{th} stress regime ............................................. 107

4-47 Changes of graph of 3 dimensional mud pressure in relation to change of azimuth with different angle of deviation of wellbore in 6\textsuperscript{th} stress regime ...................... 108

4-48 Changes of graph of 3 dimensional mud pressure in relation to change of azimuth with different angle of deviation of wellbore in 7\textsuperscript{th} stress regime ...................... 109

4-49 Mud pressure graph change in relation to change of azimuth with different angle of deviation of the wellbore in 7\textsuperscript{th} stress regime ............................................. 109

4-50 Graph of required mud pressure to drill wellbore in two regimes of normal and reverse stress with different angles of deviation and azimuth of 155 degrees .. 110

4-51 Required minimum mud pressure changes for stability of vertical wellbore based on azimuth in different stress regimes ............................................. 111

5-1 Change of required minimum mud pressure based on azimuth and angle of deviation of wellbore at point 3 ................................................................. 113

5-2 Change of required minimum mud pressure based on azimuth and angle of deviation of wellbore at point 3 ................................................................. 113
LIST OF TABLES

Table 3-1  Input parameters for the analytical program .......................... 56

Table 3-2  Numerical methods in rock mechanics engineering .............. 58

Table 4-1  Assessment of mechanical specifications of stability of wellbore walls 72

Table 4-2  Seven different cases in the Salmon oil field in order to assess the effect of stress regimes ........................................................................................................... 100
LIST OF SYMBOLS

\( \vartheta \) = Poisson coefficient
\( \alpha \) = Biot coefficient
\( E \) = Young’s coefficient
\( P_p \) = Pore pressure
\( K_{fr} \) = Module of rock bulk in dried state
\( K_s \) = Module of solid particles
\( \nu \) = Change in rock volume
\( \nu_p \) = change in rock pores
\( r \) = Radial stress
\( \sigma \) = Tangential stress
\( z \) = Axial stress
\( A \) = Radius of wellbore
\( P_w \) = Pressure inside the wellbore
\( \nu \) = Poisson ratio
\( \theta \) = Angle clockwise in relation to x axis
\( r \) = Radial stress
\( \sigma_t \) = Tangential stress
\( \sigma_a \) = Axial stress
\( \sigma_H \) = Maximum horizontal stress
\( \sigma_h \) = Minimum horizontal stress
\( \sigma_v \) = Vertical stress
\( \sigma_w \) = Wellbore radius
\(r\) = Distance from center of wellbore

\(P_w\) = Fluid pressure of wellbore wall

\(\Theta\) = Angle between one point of wellbore and the maximum horizontal stress

\(R_W\) = Radius of wellbore

\(R_f\) = Radius of the plastic region

\(R_P\) = Radius of the plastic region

\(R_e\) = Radius of the elastic region

\(r\) = Distance from the center of wellbore

\(\psi\) = Angle of expansion

\(\sigma_h\) = Homogeneous horizontal stress

\(P_i\) = Mud pressure

\(c_0\) = Pressurized strength of single axis (Mpa)

\(T_0\) = Tensile strength of single axis (Mpa)

= Porosity in percentage

= Slope of line related to \(1^\text{st} \cdot 3\), figure

\(C_0\) = Uniaxial strength which is dependent on cohesion and angle of internal friction
In the name of God
the companionate and the merciful
CHAPTER 1

INTRODUCTION

1.1 Research background

Instability in wellbore wall is one the most serious difficulties in drilling, because this can ultimately create delay in drilling operations, increase costs of drilling and in some cases can lead to abandonment of the wellbore. It is estimated that the costs related to difficulties in drilling wellbores around the world is two billion dollars a year.
Now a day, with consideration of physical and chemical characteristics of drilling we can apply necessary changes to mud composition and make the wellbore wall more stable. With assistance of the science of rock mechanics and full knowledge of characteristics of formation, optimum path to drilling wellbore and the window of mud can be calculated.

1.2 Statement of the problem

There are number of factors involved in designing wellbore when passing through different formations such as, regional in situ stress, depth of drilling, geometry of the wellbore, amount of opening pressure and existing fractures in the region and other characteristics of rock mechanics which we will deal with later. Full knowledge of these characteristics can be very effective in designing correctly. Analytical methods due to their simplicities and not requiring features related to the drilling wellbore environment that may be unknown at the beginning of project are quite applicable.

In assessing the stability of wellbore we can mention the new numerical methods which with advancement of computer software and increase in number of related parameters they are able to provide substantial assistance in assessing the stability of the wellbore and as a result reducing costs and time and at the same time increasing safety.

1.3 Objective

In this research, first of all, the stability of the wellbore 2SK5 in the salman oil field is studied in its scorpion shale layer, using analytical method (MATLAB...
software) and numerical method (FLAC3D software) with the use of the three criteria of failure of Mohr Coulomb, Mogi Coulomb and Drucker Prager.

At the same time comparisons of applications of the above criteria in relation to the wellbore stability and resultant difficulties in the process of drilling are made and ultimately recommendations to drill wellbore in the shale layer of wellbore 2SK5 in Salman oil field are presented. Also, effect of different stress regimes in specifying optimum direction and angle of deviation of the wellbore will be studied.

1.4 Scope

This research is presented in five chapters. In second chapter summary of similar activities are presented in relation to analyzing stability of wellbore and factors creating instability and summary of our solution for instability in deviational wellbores is also presented in this research.

Also, different criteria of failure are presented in second chapter. In third chapter details of algorithms of modeling and used software (MATLAB and FLAC3D) are presented.

At the beginning of fourth chapter there are some general information regarding the Salman oil field and features of lithology formations that the concerned wellbore cuts through, and properties and location of shale layer in 2SK5 wellbore is presented and then the mud window is calculated, ultimately with the use of related software study of stability of the wellbore in this shale layer takes place.