A 3-D stress and strain analysis in a three layered model with a single fractured layer: A finite element approach.

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<tr>
<th>Title</th>
<th>A 3-D stress and strain analysis in a three layered model with a single fractured layer: A finite element approach.</th>
</tr>
</thead>
<tbody>
<tr>
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Acknowledgement

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Abstract

Natural fracture systems are often influenced by the presence of different layers with contrasting rock mechanical properties. Understanding the distribution of stress between different mechanical layers is essential to the interpretation of fracture networks within these systems. Knowledge of the fracture system’s geometry and spatial distribution is crucial in understanding the planning and development of any fractured reservoir.

In this study, stress/strain distributions and deformation patterns in a three layered medium with and without pre-existing fracture set are analysed. Starting from the most simple to a complex configuration, finite element models are used to understand these patterns. Stress distribution in the presence of fractures gives a better understanding of the type of failures that the rock can undergo. Stress and strain localizations at fracture tips are observed. The study indicates that tensile stresses will result in the fractured layer in response to remote compression alone given sufficient input parameters. In this case, tensile stress arises without the requirement for an additional body force such as internal fluid pressure.

Frictional sliding (displacement) causes localization of deformation at the fracture tips. The displacement intensity varies as a function of fracture orientation (α) (α: angle between the fracture strike and the bulk compression orientation). This displacement along the fractures present in the middle layer of the model also impacts the stress distribution within the surrounding layers as well. Any change in the orientation of the remote stress may lead to significant differences in the stress magnitude within the three layers.

Similar analyses have been done with increasing complexity and the impact of fracture length, spacing and overlap/underlap between the adjacent fractures are studied. It is observed that all these parameters not only impact the stress and strain distribution within the fractured layer but also have a significant or subtle impact on the surrounding layers.

The study also aims to predict if these patterns are localized or if deformation between the fractures is also influenced by these parameters. The scenario with two fractures is therefore used to investigate the influence of one fracture on the other and it is observed that the stresses are compressive in nature and the magnitude is influenced by the fracture spacing and fracture overlap/underlap.

The study gives a confirmation on why finite element modelling is one of the better tools to do such an analysis and more importantly that it gives a first-hand understanding of the impact on such a system under external stress.
# Table of Contents

Acknowledgement ....................................................................................... iv
Abstract ........................................................................................................ vi
Table of Contents ........................................................................................ viii
Table of figures ............................................................................................... x
Table of tables ................................................................................................. xiv
Nomenclature ................................................................................................. xvii

1. Introduction .................................................................................................. 1
   1.1 Geological setting .................................................................................. 1
   1.2 Objectives ............................................................................................ 2

2. General theory .............................................................................................. 5
   2.1 Stress and strain .................................................................................... 5
   2.2 Linear elasticity ..................................................................................... 6
   2.3 Differential Stress ............................................................................... 6
   2.4 von Mises Criterion ............................................................................. 7
   2.5 Theory relevant to modelling using Ansys .......................................... 8
      2.5.1 The Drucker – Prager Plasticity model ........................................... 8
      2.5.2 CONTA174 Element Description ............................................... 9
      2.5.3 TARGE170 Element Description ................................................. 9
      2.5.4 Contact Friction ......................................................................... 10

3. Previous work ............................................................................................. 12
   3.1 Single fracture configuration ............................................................... 12
   3.2 Interaction between adjacent fractures ................................................. 15

4. Numerical Modelling .................................................................................. 17
   4.1 Basic concepts ..................................................................................... 17
      4.1.1 Boundary Element Method (BEM) .............................................. 17
      4.1.2 Finite Element Method (FEM) .................................................... 17
   4.2 The Finite Element Method ................................................................. 18
   4.3 The Finite Element Model .................................................................. 19
      4.3.1 Model set-up ................................................................................ 19
         4.3.1.1 Geometry of the model ....................................................... 20
         4.3.1.2 Material properties ............................................................ 20
         4.3.1.3 Meshing ............................................................................ 21
         4.3.1.4 Contact and friction .......................................................... 22
**Table of figures**

<table>
<thead>
<tr>
<th>Number</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fig 1.1</td>
<td>Zechstein stratigraphy in the Netherlands (H. Van Gent et al., 2011)</td>
<td>2</td>
</tr>
<tr>
<td>Fig 2.1</td>
<td>An illustration of the normal forces that are exerted on horizontal and vertical planes (Allen P. A. and Allen J. R., 2005)</td>
<td>5</td>
</tr>
<tr>
<td>Fig 2.2</td>
<td>An illustration to show the difference between von Mises and maximum shear criterion (modified from Pilkey, W. D., 1994)</td>
<td>7</td>
</tr>
<tr>
<td>Fig 2.3</td>
<td>An illustrative representation of the yield surface when plotted in principal stress space (Sheldon, 2008)</td>
<td>8</td>
</tr>
<tr>
<td>Fig 3.1</td>
<td>Four principal mechanisms of deformation localization at the tips of pre-existing shear fractures. TF: Tensile fracture; PS: Primary Shear band; and SS: Subsidiary Shear band (Misra et al., 2009)</td>
<td>12</td>
</tr>
<tr>
<td>Fig 3.2</td>
<td>Plots showing the variations of maximum tensile stress and von Mises stress as a function of crack angle and/or crack length (Misra et al., 2009)</td>
<td>13</td>
</tr>
<tr>
<td>Fig 3.3</td>
<td>Stress fields around the tips of shear cracks in FE models. (a) Principal tensile stress distribution, $\alpha = 60^0$. (b) von Mises stress distribution. $\alpha = 30^0$. (Misra et al., 2009)</td>
<td>14</td>
</tr>
<tr>
<td>Fig 4.1</td>
<td>General model set-up with a single discrete fracture and boundary conditions in a) map view and b) cross section.</td>
<td>19</td>
</tr>
<tr>
<td>Fig 4.2</td>
<td>Meshing in the case of a realistic fracture configuration where three different element sizes are used for mesh refinement.</td>
<td>22</td>
</tr>
<tr>
<td>Fig 4.3</td>
<td>Distribution of vertical ($\sigma_Y$) and horizontal ($\sigma_H$) within the model when just an overburden pressure is exerted on the layers.</td>
<td>23</td>
</tr>
<tr>
<td>Fig 4.4</td>
<td>Map view of the inner box in a multiple fracture configuration a) two parallel fractures b) 16 sub-parallel fractures.</td>
<td>24</td>
</tr>
<tr>
<td>Fig 5.1</td>
<td>An illustration to show the model set-up during the sensitivity analysis of mechanical parameters a) map view and b) cross-section</td>
<td>25</td>
</tr>
<tr>
<td>Fig 5.2</td>
<td>Differential stress distribution in the middle of each layer as a function of Young’s modulus</td>
<td>26</td>
</tr>
<tr>
<td>Fig 5.3</td>
<td>von Mises stress distribution in the middle of each layer as a function of Young’s modulus</td>
<td>27</td>
</tr>
<tr>
<td>Fig 5.4</td>
<td>Schematic representation of the orientation of the first and second principal stresses in the bottom layer when the value of Young’s modulus of the middle layer is a) less than 60 GPa and b) more than 60 GPa.</td>
<td>27</td>
</tr>
<tr>
<td>Fig 5.5</td>
<td>Differential stress distribution in the middle of each layer as a function of Poisson’s ratio</td>
<td>28</td>
</tr>
<tr>
<td>Fig 5.6</td>
<td>von Mises stress distribution in the middle of each layer as a function of Poisson’s ratio</td>
<td>29</td>
</tr>
<tr>
<td>Fig 5.7</td>
<td>Differential stress distribution in the middle of each layer as a function of overburden pressure a) in the absence of horizontal tectonic stress and b) in the presence of tectonic stress</td>
<td>30</td>
</tr>
</tbody>
</table>
Fig 5.8: von Mises stress distribution in the middle of each layer as a function of overburden pressure ................................................................. 31
Fig 5.9: Differential stress distribution in the middle of each layer as a function of applied tectonic stress .......................................................... 32
Fig 5.10: von Mises stress distribution in the middle of each layer as a function of applied tectonic stress .......................................................... 32
Fig 5.11: The model depicting the distribution of von Mises stress (in MPa) over the entire model when the simulation is run with default parameters (Table 4.1) ............... 33
Fig 6.1: Variation in displacement along the fracture surfaces as a function of orientation ($\alpha$) for different coefficient of friction (fric) values.............................................. 35
Fig 6.2: Variation in displacement along the fracture surfaces as a function of fracture length for $\alpha = 40^0$ and for a friction coefficient (fric) value of 0.3.......................... 36
Fig 6.3: A screenshot depicting the displacement (in meters) along the fracture surface when the simulation is run using default parameters (Table 4.1) and for $\alpha = 40^0$ .......... 36
Fig 6.4: Variation in plastic strain intensity at fracture tips as a function of orientation ($\alpha$) for different coefficient of friction (fric) values .................................................. 37
Fig 6.5: Variation in plastic strain intensity at fracture tips as a function of fracture length for $\alpha = 40^0$ and for a friction coefficient (fric) value of 0.3............................................. 37
Fig 6.6: A screenshot depicting the plastic strain intensity development at fracture tips when the simulation is run using default parameters (Table 4.1) and for $\alpha = 40^0$ ........... 37
Fig 6.7: Variation of $\sigma_3$ at fracture tips as a function of orientation ($\alpha$) for different coefficient of friction (fric) values............................................. 39
Fig 6.8: Variation of $\sigma_3$ at fracture tips as a function of fracture length for $\alpha = 40^0$ and for a friction coefficient (fric) value of 0.3................................................ 39
Fig 6.9: A screenshot depicting the development of tensile stress ($\sigma_3$ in MPa) at fracture tips when the simulation is run using default parameters (Table 4.1) and for $\alpha = 40^0$ .......... 39
Fig 6.10: Differential stress distribution in the middle of top layer as a function of orientation ($\alpha$) for different coefficient of friction (fric) values.......................... 40
Fig 6.11: von Mises stress distribution in the middle of top layer as a function of orientation ($\alpha$) for different coefficient of friction (fric) values ......................... 41
Fig 6.12: Differential stress distribution in the middle of bottom layer as a function of orientation ($\alpha$) for different coefficient of friction (fric) values ......................... 42
Fig 6.13: von Mises stress distribution in the middle of bottom layer as a function of orientation ($\alpha$) for different coefficient of friction (fric) values ......................... 42
Fig 6.14: Stress distributions in the middle of top and bottom layers as a function of fracture length (DS: Differential Stress; VM: von Mises stress)................................. 43
Fig 6.15: A screenshot of the map view depicting the distribution of von Mises stress (in MPa) at the middle of the top layer when the simulation is run using default parameters (Table 4.1) and for $\alpha = 40^0$ ....................................................... 43
Fig 6.16: A screenshot of the map view depicting the distribution of von Mises stress (in MPa) at the middle of the central layer when the simulation is run using default parameters (Table 4.1) and for $\alpha = 40^0$ ....................................................... 44
Fig 6.17: A screenshot of the map view depicting the distribution of von Mises stress (in MPa) at the middle of the bottom layer when the simulation is run using default parameters (Table 4.1) and for $\alpha = 40^0$ ....................................................... 44
Fig 6.18: Variation of displacement as a function of fracture spacing for $\alpha = 40^0$, friction coefficient (fric) of 0.3 and length of each fracture = 4000 m.

Fig 6.19: Variation of displacement as a function of fracture overlap for $\alpha = 40^0$, friction coefficient (fric) of 0.3 and length of each fracture = 2000 m.

Fig 6.20: A screenshot depicting the displacement (in meters) along the fracture surfaces when the simulation is run using default parameters (Table 4.1) and for $\alpha = 40^0$.

Fig 6.21: Variation of plastic strain intensity as a function of fracture spacing for $\alpha = 40^0$, friction coefficient (fric) of 0.3 and length of each fracture = 4000 m.

Fig 6.22: Variation of plastic strain intensity as a function of fracture overlap for $\alpha = 40^0$, friction coefficient (fric) of 0.3 and length of each fracture = 2000 m.

Fig 6.23: A screenshot depicting the plastic strain intensity development at fracture tips when the simulation is run using default parameters (Table 4.1) and for $\alpha = 40^0$.

Fig 6.24: Variation of $\sigma_3$ at fracture tips as a function of fracture spacing for $\alpha = 40^0$, friction coefficient (fric) of 0.3 and length of each fracture = 4000 m.

Fig 6.25: Variation of $\sigma_3$ at fracture tips as a function of fracture overlap for $\alpha = 40^0$, friction coefficient (fric) of 0.3 and length of each fracture = 2000 m.

Fig 6.26: A screenshot depicting the least $\sigma_3$ (in MPa) development at fracture tips when the simulation is run using default parameters (Table 4.1) and for $\alpha = 40^0$.

Fig 6.27: Stress values at the middle of the central layer as a function of fracture spacing.

Fig 6.28: Stress values at the middle of the central layer as a function of fracture overlap.

Fig 6.29: Variation in differential stress at the middle of top and bottom layers as a function of fracture spacing for parameters as in Table 6.3.

Fig 6.30: Variation in von Mises stress at the middle of top and bottom layers as a function of fracture spacing for parameters as in Table 6.3.

Fig 6.31: Variation in differential stress at the middle of top and bottom layers as a function of fracture overlap for parameters as in Table 6.4.

Fig 6.32: Variation in von Mises stress at the middle of top and bottom layers as a function of fracture overlap for parameters as in Table 6.4.

Fig 6.33: A screenshot of the map view depicting the distribution of von Mises stress (in MPa) at the middle of the top layer when the simulation is run using default parameters (Table 4.1) and for $\alpha = 40^0$.

Fig 6.34: A screenshot of the map view depicting the distribution of von Mises stress (in MPa) at the middle of the central layer when the simulation is run using default parameters (Table 4.1) and for $\alpha = 40^0$.

Fig 6.35: A screenshot of the map view depicting the distribution of von Mises stress (in MPa) at the middle of the bottom layer when the simulation is run using default parameters (Table 4.1) and for $\alpha = 40^0$.

Fig 6.36: A screenshot depicting the displacement (in meters) along the fracture surfaces in a single layered scenario when the simulation is run using default parameters (Table 6.5).

Fig 6.37: A screenshot depicting the displacement (in meters) along the fracture surfaces in a three layered scenario when the simulation is run using default parameters (Table 6.5).
Fig 6.38: Variation of the maximum displacement along the fracture surfaces for each of the 16 fractures, moving from left to right in single layered and a three layered scenarios

Fig 6.39: A screenshot of the map view depicting the distribution of von Mises stress (in MPa) at the middle of the top layer when the simulation is run using default parameters (Table 6.5)

Fig 6.40: A screenshot of the map view depicting the distribution of von Mises stress (in MPa) at the middle of the central layer when the simulation is run using default parameters (Table 6.5)

Fig 6.41: A screenshot of the map view depicting the distribution of von Mises stress (in MPa) at the middle of the bottom layer when the simulation is run using default parameters (Table 6.5)

Fig 6.42: A screenshot depicting the least $\sigma_3$ (in MPa) development at fracture tips when the simulation is run using default parameters (Table 6.5)
Table of tables

Table 4.1: Modelling parameters for the middle carbonate-anhydrite layer (compiled from Hangx et al., 2010¹, Schön J. H., 2011² and Pascal et al., 2001³) ............................................. 20
Table 4.2: Modelling parameters for the upper and lower halite layers (compiled from Hangx et al., 2010¹, Schön J. H., 2011² and Pascal et al., 2001³) ............................................. 21
Table 5.1: List of relevant modelling parameters used in this scenario (modified from table 4.1 and table 4.2) .................................................................................................................................................. 26
Table 5.2: List of relevant modelling parameters used in this scenario (modified from table 4.1 and table 4.2) .................................................................................................................................................. 28
Table 5.3: List of relevant modelling parameters used in this scenario (modified from table 4.1 and table 4.2) .................................................................................................................................................. 30
Table 5.4: List of relevant modelling parameters used in this scenario (modified from table 4.1 and table 4.2) .................................................................................................................................................. 31
Table 6.1: List of relevant modelling parameters used in this scenario (modified from table 4.1 and table 4.2) .................................................................................................................................................. 34
Table 6.2: List of relevant modelling parameters used in this scenario (modified from table 4.1 and table 4.2) .................................................................................................................................................. 35
Table 6.3: List of relevant modelling parameters used in this scenario (modified from table 4.1 and table 4.2) .................................................................................................................................................. 45
Table 6.4: List of relevant modelling parameters used in this scenario (modified from table 4.1 and table 4.2) .................................................................................................................................................. 46
Table 6.5: List of relevant modelling parameters used in this scenario (modified from table 4.1 and table 4.2) .................................................................................................................................................. 56
## Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
<th>Dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>Young’s modulus</td>
<td>GPa</td>
</tr>
<tr>
<td>ν</td>
<td>Poisson’s ratio</td>
<td>-</td>
</tr>
<tr>
<td>µ</td>
<td>Coefficient of friction</td>
<td>-</td>
</tr>
<tr>
<td>ρ</td>
<td>Density</td>
<td>kg/m³</td>
</tr>
<tr>
<td>g</td>
<td>Acceleration due to gravity</td>
<td>m/s²</td>
</tr>
<tr>
<td>σ</td>
<td>Stress</td>
<td>MPa</td>
</tr>
<tr>
<td>ε</td>
<td>Strain</td>
<td>-</td>
</tr>
<tr>
<td>τ_{lim}</td>
<td>Limit frictional stress</td>
<td>MPa</td>
</tr>
<tr>
<td>α</td>
<td>Fracture orientation</td>
<td>° (degrees)</td>
</tr>
<tr>
<td>P</td>
<td>Contact normal pressure</td>
<td>MPa</td>
</tr>
<tr>
<td>b</td>
<td>Contact cohesion</td>
<td>MPa</td>
</tr>
</tbody>
</table>
1. Introduction

Tectonic stresses have a profound control on the evolution of hydrocarbon reservoirs. Stresses govern the tectonic regime responsible for sedimentary basin formation and cause rock deformation, i.e., folding, faulting and fracturing. During the subsequent evolution of the reservoir rock, the regional stress fields may have changed orientation several times leading to reactivation of the existing fracture network and/or formation of new fracture sets. Particularly, the recent stresses in a reservoir have a variety of implications for exploration and production. There is a need for a thorough understanding of the reservoir geomechanics, which comprises not only of the present-day tectonic stress distribution in the reservoir, but also the mechanical properties of the reservoir rocks as well as the stress and deformation history of the reservoir leading to the fault and fracture networks observed today. Regarding the complexity of real reservoirs, such an analysis can only be provided by a numerical modelling approach. The general term “fracture” is employed here for (meso- or macro-scale) discontinuities in a rock, without assigning it a specific mode of displacement (Pollard and Aydin, 1988).

Modelling of fractured reservoirs required different techniques to the well-established geostatistical methods derived for modelling rock heterogeneity (M.C. Cacas et al., 2001). Many techniques have been applied by researchers in the recent years to understand the mechanisms and predict deformation patterns in fractured rocks, as will be discussed in detail in the chapter on ‘Previous Work’. The aim of my study is not to predict failure but to make a prediction of the stress and strain distribution within a three layered model when compressional stresses are applied. A lithological inspiration is taken from the basal Zechstein of the Netherlands.

1.1 Geological setting

The basal Zechstein is overlying the continental Slochtern and the shaly Silverpit Formation of the Rotliegendes Group. It was deposited during the Permian. In the Dutch offshore the Formation lies around a depth of 3300 – 4700 m that forms a lateral extensive deposit onshore and offshore. After a regional subsidence, desert conditions changed when the Aeolian Lower Permian sediments were transgressed by the Zechstein Sea. The base of the Zechstein Formation is marked by the Kupferschiefer shale and is overlain by five main sedimentary-evaporite cycles of the Zechstein (Z1 – Z5). Each evaporate cycle is the result of a marine transgression that is succeeded by a regression and reflects the effect of the increasing salinity.

In the Dutch subsurface, the Zechstein can be subdivided in a marine lower part (Z1 – Z3) and a playa-type upper part (Z4 and Z5) with more clastic deposits (Geluk, 1997, 2000). Z1 – Z3 follow the classic carbonate-evaporite cycle; claystone-carbonate-gypsum-halite-potassium and magnesium salts consecutively (Geluk, 2000). The cycles correspond to major transgressions
from the North and evaporation of seawater in the arid Southern Permian Basin (Fig 1.1, Taylor, 1998). In the northern Netherlands deposition was relatively continuous, but the sedimentary sequence has major periods of non-deposition in the south (Geluk, 2007).

My study focuses on the relatively brittle, claystone-carbonate-anhydrite layer (the Z3 stringer) enclosed in ductile salt. Z3 stringers are reservoirs for hydrocarbons. The stringers usually have a thickness of about 40 m, with areas of increased thickness of up to 150 m (H. Van Gent et al., 2011).

The top Zechstein is relatively horizontal at 2000 – 2200 m. Thickness of Zechstein is about 1000 m, increasing up to 2000 m in the salt pillows (H. Van Gent et al., 2011). Although the original stratigraphic position of the Z3 stringer is about 200 – 300 m below top Zechstein, in its present geometry its position varies from very close to top Zechstein, to very close to top Z2 anhydrite.

1.2 Objectives

Getting inspiration from the basal Zechstein lithology, the study aims to answer the gaps in understanding the stress and strain distribution over a three layered model using a finite element approach. This study though, mainly considers this case study as a “lithological analogy” to estimate the input mechanical parameters for the model.

The model; which will be discussed in detail in the fourth chapter; primarily comprises of three blocks on top of each other, with contrasting mechanical properties. Stresses (overburden and tectonic) are gradually applied on this
model in the form of different load steps. The tectonic stress is horizontal and is applied from one direction (Fig 4.1). The model thus, is subject to boundary conditions in each of the scenarios with increasing complexity. Analysis is then done on the stress and strain distribution over the entire model when it is subjected to the above conditions.

All of the previous work on such analyses have been restricted to a single layered model and significant work has not been done to study if the changes within the fractured layer will have an impact on the surrounding layers. Previous work too concentrated on the stress/strain localization at fracture tips but I also try to look at the distribution between the fractures. A question also arises that if changes are made to one of the mechanical layers (central layer in our case), will it have an impact on the stress and strain distribution over the surrounding layers as well? To answer this and similar questions, series of simulations are run using the finite element software ANSYS (academic research, release 12.0).

As mentioned before, the study is done with an increasing complexity of the model; all with three layers. In the first set of scenarios, I try to answer if the change in mechanical parameters within the central layer alone have an impact over the entire model. In this scenario, only changes to the mechanical parameters are made while the model is still subject to external stresses at their default chosen values (Tables 4.1 and 4.2). In the second simple case, I change the magnitudes of applied stresses on the model. I first study the impact of overburden pressure alone, in the absence of tectonic stress and then look at the case when the same analysis is done in the presence of tectonic stress. The final study in this scenario is to change the magnitude of tectonic stress while the model is assumed to be at a depth; which is comparable to the case study. As a boundary condition an overburden pressure of 60 MPa is applied at the top of the model, which is equivalent to a depth of around 2.2 km.

By increasing the complexity by a notch in the next scenarios, I include a fracture in the central layer. I not only look at the impact of the fracture orientation (α), friction coefficient (µ) and fracture length (l) on the patterns at fracture tips and on the fracture surface but also try to see if they have an impact on the other layers as well. With a further increase in complexity, I now consider a case with two parallel fractures in the central layer. Here, I will look at the impact of fracture spacing and fracture overlap/underlap to not only answer similar questions but to also see if there is an impact of these parameters on the stress/strain distribution between the fractures. The final complex scenario comprises of a realistic fracture orientation within the central layer. This is merely used to compare the differences between the model run as a single layered scenario and a model run as a three layered scenario.

The geological characteristics of fracture networks and the type of data available put severe constraints on the design of modelling procedure. But the study will
try to justify how the finite element modelling techniques can be applied in such case studies to give us a preliminary understanding of the stress and strain distribution in such a system. Propagation of the pre-defined fractures or the birth of new discrete discontinuities is not considered in this study; instead, the focus is on the resulting stress and strain distributions as indicators for potential fracture and shear band development while also concentrating on the changes within the surrounding layers.
2. General theory

This chapter deals with some of the basic theoretical concepts that are encountered in the course of the subsequent chapters.

2.1 Stress and strain

Body forces on an element of a solid act throughout the volume of the solid and are directly proportional to its volume or mass. For example, the force of gravity per unit volume is the product of \( \rho \), the density and \( g \), the acceleration due to gravity. The body forces on rocks within the Earth’s interior depend on their densities, but density in itself a function of pressure. Surface forces act only on the surface bounding a volume. The magnitude of the force depends on the surface area over which the force acts and the orientation of the surface. If we consider the case of vertical stress, the normal component of force per unit area, or stress on horizontal planes increases linearly with depth. That due to the weight of the rock overburden is known as lithostatic or overburden pressure.

Normal forces can also be exerted on vertical planes as seen in Fig 2.1.

![Fig 2.1: An illustration of the normal forces that are exerted on horizontal and vertical planes (Allen P. A. and Allen J. R., 2005)](image)

The normal stresses \( \sigma_{xx}, \sigma_{yy} \) and \( \sigma_{zz} \) are rarely equal when a rock mass is subjected to overburden pressure or is being subjected to tectonic forces. Tectonic forces are those originating beneath the surface that alter the surface configuration of the earth as a result of tectonic (lithospheric) plate movement.

Normal stresses can be either tensile when they tend to pull on planes or compressive when they push on planes. Stress components can be generalized at any point in a material by using the x, y, z coordinate system. At any point, we can envisage three mutually perpendicular planes on which there are no shear stresses. Perpendiculars to these planes are known as principal axes of stress and can be labelled as,
\( \sigma_1 \) – maximum principal stress
\( \sigma_2 \) – intermediate principal stress
\( \sigma_3 \) – minimum principal stress,

where convention is that \( \sigma \) is positive for compressional stress and negative for extensional stress.

Strain is the deformation of a solid caused by the application of stress. We can define the components of strain by considering a rock volume with sides \( \delta_x \), \( \delta_y \) and \( \delta_z \) which changes in dimensions but not in shape, so that the new lengths of the sides after deformation are \( \delta_x - \varepsilon_{xx} \delta_x \), \( \delta_y - \varepsilon_{yy} \delta_y \) and \( \delta_z - \varepsilon_{zz} \delta_z \) where \( \varepsilon_{xx} \), \( \varepsilon_{yy} \) and \( \varepsilon_{zz} \) are the strains in the \( x \), \( y \) and \( z \) directions. Volume elements may also change their position without changing their shape, in which case the strain components are due to displacement. Shear strains, however, may distort the shape of an element of a solid.

Plastic Strain Intensity (PSI) is defined as the largest of the absolute values of \( \varepsilon_1 - \varepsilon_2 \), \( \varepsilon_2 - \varepsilon_3 \) or \( \varepsilon_3 - \varepsilon_1 \).

\[
PSI = MAX(|\varepsilon_1 - \varepsilon_2|,|\varepsilon_2 - \varepsilon_3|,|\varepsilon_3 - \varepsilon_1|)
\]

Strain Intensity can be related to shear strains which is why it is measured at fracture tips in my study to give us an idea about straining due to shearing.

2.2 Linear elasticity

It is clearly important to know the relationship between the stress and strain. These relationships reflect the basic flow laws of Earth materials. Elastic materials deform when they are subjected to a force and regain their original shape and volume when the force is removed. The relation between stress and elastic strain is linear.

If we consider the case where stress is applied to a linear, isotropic and elastic solid, the strain is linearly proportional to the stress. An isotropic solid means that the mechanical properties associated with it have no preferred orientation. The principal axes of stress and the principal axes of strain coincide. The exact partitioning of stresses to give a resultant strain is clearly strongly influenced by \( E \) and \( \nu \), which are material properties known as Young’s modulus and Poisson’s ratio respectively. In general terms, a principal stress produces a strain component \( \sigma/E \) along the same axis and strain components \( -\nu\sigma/E \) along the other orthogonal axes.

2.3 Differential Stress

Differential stress is the difference between the greatest and the least compressive stress experienced by an object.

\[
\sigma_D = \sigma_1 - \sigma_3
\]
In structural geology, differential stress is used to assess whether tensile or shear failure will occur. Through this study, differential stress values are measured at the required points within the model as these values are useful to go ahead and predict the failure based on the Maximum Shear theory. This would of course require the information on yield/failure stresses.

For example, tensile failure occurs when the Mohr circle described by the differential stress intersects with the failure envelope of the material in the tensile regime ($\sigma_D < 4T$, $T$ is the material tensile strength), requiring at least a negative value of $\sigma_3$ (Jaeger et al., 2007). Thus, differential stress measurements will give us an initial idea of the failure criteria.

### 2.4 von Mises Criterion

A single failure theory may not always apply to the given material. The von Mises Criterion (1931) gives another reasonable estimation of failure. It is also known as the maximum distortion energy criterion, octahedral shear stress theory, or Maxwell-Huber-Hencky-von Mises theory, is often used to estimate the yield of ductile materials. Distribution of von Mises stress over the tensile and/or compressive regimes can also be used as criteria to understand the failure mechanisms.

The von Mises criterion states that failure occurs when the energy of distortion reaches the same energy for yield/failure ($\sigma_y$) in uniaxial tension. Mathematically, this is expressed as,

$$\frac{1}{2}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2] \leq \sigma_y^2$$

This equation represents a principal stress ellipse as illustrated in Fig 2.2.

---

**Fig 2.2:** An illustration to show the difference between von Mises and maximum shear criterion (modified from Pilkey, W. D., 1994)
Also shown in the figure is the maximum shear stress criterion (dashed line). This theory is more conservative than the von Mises criterion since it lies inside the von Mises ellipse. In addition to bounding the principal stress to prevent ductile failure, the von Mises criterion also gives a reasonable estimation of fatigue failure, especially in cases of repeated tensile and tensile – shear loading. However, in the case of a situation where hydrostatic stresses play a role in failure, this criterion is not very efficient.

2.5 Theory relevant to modelling using Ansys

The following sections deal with the description of some of the common aspects that are involved as part of modelling using Ansys.

2.5.1 The Drucker – Prager Plasticity model

The Drucker – Prager plasticity model is different from typical metal plasticity models since it contains a dependence on hydrostatic pressure. For metal plasticity (assuming Mises or similar yield surface), only the deviatoric stress is assumed to cause yielding – if we plot the yield surface in principal stress space, this results in a cylinder whose axis is the hydrostatic pressure line, indicating that yielding is independent of the hydrostatic stress state. For the Mises yield surface, theoretically, one could have infinite hydrostatic compression and no yielding would occur.

On the other hand, the Drucker – Prager plasticity model has a term that is dependent on the hydrostatic pressure. For a linear yield surface (“linear” referring to the linear shape when plotted in the plane of effective stress vs. hydrostatic pressure), this means that is there is some hydrostatic tension, the yield strength would be smaller. Conversely, as hydrostatic compression increases, so would the yield strength. When the yield surface is plotted in principal stress space, it would look like a cone as shown in Fig 2.3.

![Fig 2.3: An illustrative representation of the yield surface when plotted in principal stress space (Sheldon, 2008)](image-url)

The two main characteristics that result are that (a) the yield strength changes depending on the hydrostatic stress state and (b) some inelastic volumetric strain can occur, as defined by the flow potential. Due to these points, the
Drucker–Prager material model is used for geomechanics where both hydrostatic dependence and inelastic volume strain are important.

Ansys supports the use of three Drucker–Prager models:

a) Drucker–Prager model
b) Extended Drucker–Prager model
c) Drucker–Prager Cap model

For the current analysis, the extended Drucker–Prager model is used. This model addresses some of the shortcomings of the Drucker–Prager model, namely, the use of perfectly-plastic behaviour and the requirement of a linear yield surface. Strain-hardening behaviour is specified by adding an isotropic hardening plasticity model to the same material ID.

To simulate the effects of the presence of fractured surfaces in the model, Ansys uses the concept of generating the contact and target surfaces. This is primarily done to simulate the sliding between the 3D surfaces that define a fracture. The subsequent sections deal with the description of contact and target elements used to simulate our requirements. The idea of friction between the two surfaces is also important for our analysis.

2.5.2 CONTA174 Element Description

It is a 3-D 8-Node Surface-to-Surface Contact. CONTA174 is used to represent contact and sliding between 3-D “target” surfaces (TARGE170) and a deformable surface, defined by the element. The element is applicable to 3-D structural and coupled field contact analysis. Contact occurs when the element surface penetrates one of the target segment elements (TARGE170) on a specified target surface. Coulomb friction, shear stress friction, and user-defined friction with the USERFRIC subroutine are allowed. This element also allows separation of bonded contact to simulate interface delamination.

CONTA174 supports isotropic and orthotropic Coulomb friction. For this analysis, an isotropic Coulomb friction is assumed by assigning a single coefficient of friction. The 3-D contact surface elements (CONTA174) are associated with the 3-D target segment elements (TARGE170) via a shared real constant set. ANSYS looks for contact only between surfaces with the same real constant set. For either rigid-flexible or flexible-flexible contact, one of the deformable surfaces must be represented by a contact surface.

2.5.3 TARGE170 Element Description

TARGE170 is used to represent various 3-D “target” surfaces for the associated contact elements. The contact elements themselves overlay the solid, shell, or line elements describing the boundary of a deformable body and are potentially in contact with the target surface, defined by TARGE170.
This target surface is discretized by a set of target segments elements and is paired with its associated contact surface via a shared real constant set.

The target surface can either be rigid or deformable. For modelling rigid-flexible contact, the rigid surface must be represented by a target surface. For flexible-flexible contact, one of the deformable surfaces must be overlain by a target surface. Each target surface can be associated with only one contact surface, and vice-versa. However, several contact elements could make up the contact surface and thus come in contact with the same target surface. Likewise, several target elements could make up the target surface and thus come in contact with the same contact surface.

2.5.4 Contact Friction

Coulomb’s Law – In the basic Coulomb friction model, two contacting surfaces can carry shear stresses. When the equivalent shear stress is less than a limit frictional stress (τlim), no motion occurs between the two surfaces. This state is known as sticking. The Coulomb friction model is defined as:

\[ \tau_{\text{lim}} = \mu P + b \]

Where \( P \) is contact normal pressure, \( \mu \) is the friction coefficient and \( b \) is the contact cohesion.

Once the equivalent frictional stress exceeds \( \tau_{\text{lim}} \), the contact and target surfaces (defined by CONTA174 and TARGE170 elements) will slide relative to each other. This state is known as sliding. The sticking/sliding calculations determine when a point transitions from sticking to sliding or vice versa. The contact cohesion provides sliding resistance even with zero normal pressure.

Contact friction is a material property used with the chosen contact element of CONTA174. It may be specified either through the coefficient of friction (\( \mu \)) for isotropic or orthotropic friction models or as a user defined friction properties.

a) Isotropic Friction – The isotropic friction model uses a single coefficient of friction based on the assumption of uniform stick-slip behaviour in all directions. Isotropic friction is applicable to 2-D and 3-D contact and is available for all contact elements. Using the TB.FRIC command with TBOPT=ISO, we can define the isotropic friction, and later on the coefficient of friction \( \mu \) is specified.

b) Orthotropic Friction – The orthotropic friction model is based on two different coefficients of friction, to model different stick-slip behaviour in different directions. It is applicable only to 3-D contact. The two
coefficients are defined in two orthogonal sliding directions called the principal directions. Using the TB,FRIC command with TBOPT=ORTHO defines the orthotropic friction, and later on the coefficients of friction, $\mu_1$ and $\mu_2$ are to be specified.
3. Previous work

This chapter highlights the work done in the field of geomechanical modelling till date. It is quite important to understand how the previous researchers have tried to answer the various questions that arise during the course of their research. Based on their contributions, an attempt is made to correlate my research with their work and also try to answer some intriguing questions that arise when dealing with more complex scenarios.

Reactivation of pre-existing fractures in the presence of compressional shear loading conditions usually involves frictional sliding along the fracture walls (Misra et al., 2009). Sliding along the fracture planes produces local tensile stress concentrations that can cause the propagation of wing cracks, also called as tail or splay fractures (Willemse et al., 1997). Several analytical (Willemse and Pollard, 1998), experimental (Misra et al., 2009) and numerical methods (Bourne and Willemse, 2001; Maerten et al., 2002; Lunn et al., 2008) can help us understand the mechanisms and predict deformation patterns in fractured rocks.

3.1 Single fracture configuration

Considering the experimental and numerical methods, finite element method (FEM) has been widely used to simulate the above effects. Misra et al. (2009) describe four deformation localization mechanisms at the tips of pre-existing planar shear cracks based on analogue experiments with photo elastic models and finite element models (Fig 3.1). Wing fractures are a common variety of secondary structures that emanate from the tips of shear cracks or weak surfaces. They develop in response to the local tensile stress concentration. Wing fractures can open out, and form fissures tapering away from the shear crack tip. During their growth the fractures change the propagation direction, and become curvilinear in geometry. Wing cracks are more prominent in brittle mechanism whereas the shear bands are more prominent in ductile mechanism. Fracture failure doesn’t necessarily occurs in the case of pure ductile mechanism.

Fig 3.1: Four principal mechanisms of deformation localization at the tips of pre-existing shear fractures.
TF: Tensile fracture; PS: Primary Shear band; and SS: Subsidiary Shear band (Misra et al., 2009)
Mechanism A to Mechanism D exhibit a continuous transition from brittle to ductile deformation localization patterns with increasing flaw and the bulk compression direction (\(\alpha\)). The displacement along the reactivated fracture surfaces can be one of the primary causes for this behaviour. Mechanism A involves brittle deformation as the dominant process that forms a pair of long tensile fractures at the crack tips. The tensile fractures propagate along the compression direction and transgress the entire model thickness, causing model failure at a small bulk strain (3\%). Mechanism B involves both brittle and ductile (plastic) strain localization, where the tensile fractures grow to a limited length and incipient ductile zones appear at the tips. Mechanism C is where deformation localization is characterized by an association of macro scale shear bands and short, opened-out tensile fissures (cf. wing fractures). Mechanism D involves ductile strain localization in the form of a pair of shear bands at each tip. Fracture failure does not occur in this case.

Plastic zones are considered to develop following the von Mises stress localization. Numerical modelling is done to understand the variation of maximum tensile stress with crack angle (\(\alpha\)) (\(\alpha\): angle between the fracture strike and the bulk compression orientation) (Fig 3.2.a) and crack length (\(l\)) (Fig 3.2.b) respectively. Variation of maximum tensile stress with crack angle (\(\alpha\)), keeping a constant crack tip distance from the model boundary (Fig 3.2.c) and also the variation of maximum von Mises stress with crack angle (\(\alpha\)) (Fig 3.2.d) are plotted as well.

![Fig 3.2: Plots showing the variations of maximum tensile stress and von Mises stress as a function of crack angle and/or crack length (Misra et al., 2009)](image)
Finite element modelling on Ansys has also been done by Misra et al. (2009). Fig 3.3 shows the stress field distributions around fracture tips. This is primarily used to understand the localization mechanisms at fracture tips.

Fig 3.3: Stress fields around the tips of shear cracks in FE models. (a) Principal tensile stress distribution, $\alpha = 60^\circ$. (b) von Mises stress distribution, $\alpha = 30^\circ$. (Misra et al., 2009)
Running such simulations give us a good understanding of reactivation mechanisms of existing fractures and the fracture propagation patterns. Formation of wing cracks and/or shear bands has been well understood through these simulations and correlation with field analogues.

3.2 Interaction between adjacent fractures

Observed geometries of joints indicate the widespread occurrence of mechanical interaction. The effect of mechanical interaction between nearby joints is highlighted by many researchers (Pollard and Aydin, 1988; Willemse et al., 1996). Joint geometry, suggests that mechanical interactions between nearby joints or between a joint and a local heterogeneity influence joint growth and arrest, and consequently, joint pattern and spacing (Pollard and Aydin, 1988). The mechanical interaction of joints also helps to rationalize the ratio of overlap to separation of echelon joints, their hook-shaped geometry, and the length distribution of joints in a set. In addition, interaction can explain why some joints selectively terminate, whereas others propagate, and why joints stop before or at some bedding interfaces but cur across others. Also, mechanical interaction between faults segments leads to systematic deviations from simple symmetric slip distributions (Willemse et al., 1996). Interaction between neighbouring segments can cause off-centre location of maximum slip, asymmetrical slip gradients along under-lapping segments, decrease of slip gradients in the relay zone between overlapping segments, and kinematic coherence of fault arrays. The effects of interaction become more pronounced with increasing segment overlap (Fig 3.4).

Among those who worked on numerical modelling, the effect of local stress perturbation on secondary fault development has been studied by Maarten et al. (2002) and the simulations on brittle fault growth from linkage of pre-existing structures has been studied by Lunn et al. (2008). Simulations show that linkage geometries are governed by three key factors: the stress ratio; the original joint geometry, such as contractional or dilational configurations; and the orientation of the principal stress (Lunn et al., 2008). Numerical modelling has been used to predict
fault zone geometries, and hence, identify the most (and least) likely structures for promoting fluid flow. Linkage between overlapping and underlapping joints has also been studies in detail by Lunn et al. (2008).

It is evident that substantial amount of work has been done in the geomechanical modelling of fractured lithologies. Most of the work also aims at studying stress/strain localization at fracture tips but I also make an attempt to study the distribution of stress/strain between the fractures. My study aims to work on a multi-layered tectonic scenario which not only tries to relate to the results of previous work in this field, but also tries to understand the effects of these parameters on the overlying/underlying layers.
4. Numerical Modelling

4.1 Basic concepts

Various numerical techniques have been applied to the prediction of stress/strain distribution and fracture patterns (Bourne and Willemse, 2001; Maerten et al., 2002; Lunn et al., 2008). The two widely used approaches to numerical modelling are boundary element (BEM) and finite element methods (FEM). A brief distinction between these two methods is made below:

4.1.1 Boundary Element Method (BEM)

The main advantage of the BEM is that only surfaces e.g. faults, have to be discretized but not the intervening rock volumes. This reduces the problem by one dimension i.e., from 3D to 2D. Two types of boundary conditions are used for the BEM. The local boundary conditions applied to the fault plane elements represent the slip distribution on the fault, which can be derived, for example, from interpretation of 3D seismic. The second type of boundary condition represents the regional stress field and can be applied as remote stress or strain. The BEM allows to represent complex fault geometries and subsurface structures with a large number of faults, respectively. Regarding real rock mechanical behaviour and the mechanical stratigraphy of reservoirs, limitations of the BEM are the linear-elastic material law and the required homogeneity of the model.

4.1.2 Finite Element Method (FEM)

The FEM has numerous applications for engineering purposes, but several commercial software packages like Abaqus and Ansys, among others, have also been applied successfully to geoscientific topics. This numerical method allows calculation of stresses and strains for heterogeneous structures with complex geometries and non-linear material behaviour, that is well suited for geomechanical reservoir modelling. In contrast to the BEM, FEM describes rock mechanics more realistically and allows a full three-dimensional representation of the subsurface. However, FEM reservoir models with a large number of faults are demanding with respect to model generation and computing time.

In this study, FEM technique is applied and the steps involved are discussed in the subsequent sections.
4.2 The Finite Element Method

The common steps involved in a finite element analysis are as follows:

a. Discretization – In the discretization phase, the domain is divided into finite number of regularly shaped elements. Each of these elements consists of nodal points which have known coordinates within the global coordinate system. The shape of each element is defined in relation to its nodal point coordinates and interpolation or shape functions.

b. Element Formulation – An interpolation function is assumed for the variation of the unknown across each element. This unknown can vary, but is dependent on the nature of the analysis. In some analysis, the unknown may be stress, in others displacement and so on. Coefficient matrices are determined for each element which describe the responses of the element in question. In a stress analysis, the matrix corresponds to the element stiffness matrix.

c. Transformation of Element Equations – The element stiffness matrices are naturally aligned with their corresponding element local coordinate system. In order to solve the problem, these matrices must be transformed so that they are aligned with the global coordinate system.

d. Assembly of Global Element Equations – The transformed element matrices are now gathered together to form a global stiffness matrix that describes the behaviour of the entire problem domain.

e. Application of boundary conditions – To solve the problem, some of the nodal unknowns must be constrained. In other words, boundary conditions in a model must explicitly represent everything in the operating environment that is not explicitly modelled. Moreover, boundary conditions must never restrict or allow deformations that would not be restricted or allowed by the unmodelled parts they represent. They are applied as constraints and loads. Typically loads are used to represent inputs to the system of interest, in the form of forces, moments, pressures, temperatures or accelerations. Constraints, on the other hand, are typically used as reactions to the applied loads.

f. Solution phase – The nodal unknowns are determined by simultaneously solving the set of linear or non-linear algebraic matrix equations. The solution phase obtains values of the dependent variable at the location of each node.

g. Post processing – Further manipulation of nodal values and interpolation functions obtains secondary or derived quantities such as stresses and strains.
4.3 The Finite Element Model

In this study, the model is created and solved using the finite element software ANSYS (academic research, release 12.0). Every command used to build the model were stored in an input file. The code of the input file is adjusted so that the model is defined in terms of parameters. The aspects of the model such as geometry, material properties, mesh size, contact and loading conditions are defined as parameters which are created at the beginning of the input file.

It is often necessary to delete numerous features of the model before any adjustments can be made. For example, in a fully meshed model, to make changes to the geometry the mesh must be cleared together with any boundary conditions on the nodes. Once the change is made, all of the features must be reapplied. This is quite a time consuming exercise. To overcome this issue, the concept of running the model through the well-defined input file is used. All aspects of the model including material models, element formulation, meshing and boundary conditions are included in this file. The various steps involved in this process, along with the choices made are outlined below.

4.3.1 Model set-up

Fig 4.1: General model set-up with a single discrete fracture and boundary conditions in a) map view and b) cross section.
4.3.1.1 Geometry of the model

The model comprises of three blocks. The model is first built as three 5 km x 5 km x 0.5 km blocks stacked on top of each other and for each of these blocks, outer blocks of 20 km x 20 km x 0.5 km are built. The horizontal dimensions of the outer box are significantly larger than the fracture lengths (≥ 5 times) to minimize boundary effects (Misra et al., 2009). In the case of the scenarios with fractures in the middle layer, the geometry of the inner block is a bit complicated though. The inner blocks are constructed as combinations of smaller blocks, depending on the number of fractures, to form the entire inner block. Only in the case of the realistic fracture configuration, each block comprises of an inner, intermediate and an outer block. This division of the whole model into blocks is done to obtain a gradual increment in element size from the inner block towards the model edges. Another important reason for this approach is to achieve a change in angle between fracture surfaces and the applied tectonic stress by simply rotating the inner block while the compression (horizontal) is always applied on the outer block, along the y-axis.

4.3.1.2 Material properties

The inner and outer blocks of each layer have been assigned the same material properties, that are representative for carbonate-anhydrite Z3 stringers (Table 4.1) and the enclosing halite layers (Table 4.2). Mean values from a range of values compiled from literature are listed below which are used as default parameters in the series of simulations.

Table 4.1: Modelling parameters for the middle carbonate-anhydrite layer (compiled from Hangx et al., 2010¹, Schön J. H., 2011² and Pascal et al., 2001³)

<table>
<thead>
<tr>
<th>Elastic material properties</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (ρ)</td>
<td>2860 kg/m³</td>
</tr>
<tr>
<td>Young’s modulus (E)</td>
<td>50 GPa</td>
</tr>
<tr>
<td>Poisson’s ratio (v)</td>
<td>0.27</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Inelastic material properties</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Failure criterion</td>
<td>EDP</td>
</tr>
<tr>
<td>Cohesion (c)</td>
<td>24.6 MPa</td>
</tr>
<tr>
<td>Tang. modulus</td>
<td>E/100</td>
</tr>
<tr>
<td>Friction angle (ϕ)</td>
<td>32°</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fracture properties</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Friction coefficient (μ)</td>
<td>0.3</td>
</tr>
<tr>
<td>Fracture length (l)</td>
<td>4000 m</td>
</tr>
<tr>
<td>Fracture spacing</td>
<td>500 m</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Applied compressive stress</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Tectonic pressure (σ_H)</td>
<td>80 MPa</td>
</tr>
</tbody>
</table>
Table 4.2: Modelling parameters for the upper and lower halite layers (compiled from Hangx et al., 2010\textsuperscript{1}, Schön J. H., 2011\textsuperscript{2} and Pascal et al., 2001\textsuperscript{3})

<table>
<thead>
<tr>
<th>Elastic material properties</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (ρ)</td>
<td>2160 kg/m³</td>
</tr>
<tr>
<td>Young’s modulus (E)</td>
<td>30 GPa</td>
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<tr>
<td>Poisson’s ratio (ν)</td>
<td>0.25</td>
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</table>

<table>
<thead>
<tr>
<th>Inelastic material properties</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Failure criterion</td>
<td>EDP</td>
</tr>
<tr>
<td>Cohesion (c)</td>
<td>8.21 MPa</td>
</tr>
<tr>
<td>Tang. modulus</td>
<td>E/100</td>
</tr>
<tr>
<td>Friction angle (ϕ)</td>
<td>25°</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Applied compressive stress</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Tectonic pressure\textsuperscript{+} (σ_H)</td>
<td>80 MPa</td>
</tr>
<tr>
<td>Overburden pressure (σ_V)</td>
<td>60 MPa (approx. 2.2 km)</td>
</tr>
</tbody>
</table>

Extended Drucker - Prager failure criterion with a linear yield function, linear associative flow potential and bi-linear isotropic hardening is used to account for “strengthening” of rocks as a result of increasing confining pressure with depth (Jaeger et al., 2007).

4.3.1.3 Meshing

Discretization is done by using a free mesh on the model. A free mesh has no restrictions in terms of element shapes, and has no specified pattern applied to it. Meshing is done with 3-D tetrahedral elements interconnected by nodes, with different element sizes for the inner and outer blocks. Element size of 250 m is used for discretizing all the three inner blocks while an element size of 1000 m is used in the case of the outer blocks of all the scenarios except for the realistic fracture configuration scenario where this element size is used for the intermediate block. The outermost block in this scenario is discretized with elements of size 3000 m (Fig 4.2). The main reason for this mesh refinement is to ensure sufficient accuracy in the area of interest while also limiting the computation time.
4.3.1.4 Contact and friction

Contact elements allow for differential displacements between the independently meshed fracture blocks of the model. An automatic surface to surface contact algorithm is used to define the surfaces along the fractures. CONTA174 and TARGE170 element types have been used to define the contact and target surfaces. As a part of this contact algorithm, default friction coefficient value (Table 4.1) is assigned. A discrete fracture in the inner box is composed of opposing contact elements with an associated uniform friction coefficient (Misra et al., 2009).

4.3.1.5 Boundary conditions and loading

The base of the model and three vertical edges of the model are constrained from vertical and horizontal displacements respectively. The external loads are applied in multiple and consecutives steps; i) the model is first pre-stressed under its own gravitational field, ii) the model is put at a depth by adding an overburden pressure ($\sigma_V$) to the top of the model, and iii) horizontal tectonic pressure ($\sigma_H$) is applied to the unconstrained vertical edge.

Fig 4.3 illustrates the distribution of vertical ($\sigma_V$) and horizontal ($\sigma_H$) stresses within the model when it is put at a depth (Step ii above).
4.3.2 Modelling strategy

The pre-defined fractures in the inner box are all straight, smooth and vertical while the fracture length, spacing and orientation (α) are varied for different configurations. Four different scenarios with increasing complexity are tested in this study. The most complex scenario comprises of 16 fractures.

(i) The first simple scenario is one without fractures. This model is designed to test the influence of mechanical parameters and the applied stresses on the stress distribution within the model. A simple 3 layered model is constructed with inner and outer boxes for each layer. This is captured as a sensitivity analysis on the modelling parameters including the applied stresses.

(ii) The second scenario comprises of a single fracture in the centre of the middle layer. The model response to variations in fracture length and friction coefficient along with a change in the orientation (α) of the fracture with respect to the applied tectonic stress is investigated. The inner box is rotated by angle α along the central z-axis in steps of 10° ranging from 0° to 90°. The illustration seen in Fig 4.1 depicts the model set-up in the case of a single fracture configuration along with the boundary conditions.

(iii) The third scenario comprises of an echelon configuration of two fractures that are parallel to each other. The effect of fracture spacing and fracture overlap is investigated through this scenario. A constant orientation (α) of 40° is chosen along with a constant value of 0.3 for friction coefficient (μ). Fracture spacing is defined as the fracture perpendicular distance between the fracture planes. Fracture overlap is defined as the fracture-parallel distance between fracture terminations T1 and T2; positive for fracture overlap and negative for fracture underlap (Willemse et al., 1996; Lunn et
al., 2008). The illustration of the inner box in a two-fracture configuration is shown in Fig 4.4.a

(iv) The fourth scenario comprises of complex fracture configuration with a geologically realistic variability of fracture orientation (\( \pm 10^0 \) from the mean), length (~600-5000 m), and spacing (~50-350 m) (Fig 4.4.b). This configuration is adapted from large-scale fracture swarms (first order fracture zones striking N65\(^0\)) traced on high-resolution satellite imagery near Petra, Jordan (Strijker et al., submitted).
5. Sensitivity analysis

This chapter is primarily aimed to do a sensitivity analysis on the different parameters within the model in the absence of any fractures. Throughout this chapter and the subsequent chapters, the term ‘layer’ is used instead of ‘block’ that was used in the previous chapter on numerical modelling concepts and strategies. This transformation is made to make a distinction between the concept and geology as the term ‘layer’ is analogous to a ‘geological layer’. Two different scenarios are analysed in detail as below:

5.1 Variation of mechanical parameters

The first scenario is to compare the effect of variations in mechanical parameters like Young’s Modulus and Poisson’s ratio of the middle layer on the stress distribution over the model. These values are chosen to be around the realistic values of these parameters for the chosen case study (Table 4.1). The depth of the model in these simulations is at around 2.2 km and a constant tectonic stress of 80 MPa is applied (Fig 5.1).

![Diagram showing model set-up during sensitivity analysis of mechanical parameters](image)

Fig 5.1: An illustration to show the model set-up during the sensitivity analysis of mechanical parameters

a) map view and b) cross-section
5.1.1 Variation of Young’s modulus

The Young’s modulus of the middle layer is varied from 30 GPa to 70 GPa in steps of 10 GPa while the Young’s moduli of the top and bottom layers are maintained at the same value (Table 5.1).

Table 5.1: List of relevant modelling parameters used in this scenario (modified from table 4.1 and table 4.2)

<table>
<thead>
<tr>
<th>Modelling parameters</th>
<th>Top layer</th>
<th>Middle layer</th>
<th>Bottom layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (ρ)</td>
<td>2160 kg/m³</td>
<td>2860 kg/m³</td>
<td>2160 kg/m³</td>
</tr>
<tr>
<td>Young’s modulus (E)</td>
<td>30 GPa</td>
<td>30 – 70 GPa</td>
<td>30 GPa</td>
</tr>
<tr>
<td>Poisson’s ratio (ν)</td>
<td>0.25</td>
<td>0.27</td>
<td>0.25</td>
</tr>
<tr>
<td>Tectonic stress (σ_H)</td>
<td>80 MPa</td>
<td>80 MPa</td>
<td>80 MPa</td>
</tr>
<tr>
<td>Overburden pressure (σ_V)</td>
<td>60 MPa</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

The first noteworthy observation is on the differential stress within the layers. It is noticed that the differential stresses, measured at the middle of each layer, increases with an increase in the Young’s modulus in the middle layer while in the top and bottom layers fall consistently, as seen in Fig 5.2.

![Fig 5.2: Differential stress distribution in the middle of each layer as a function of Young's modulus](image)

Young’s modulus has a big impact on the horizontal compressive stress which is the maximum principal stress (σ₁). Contrast in the Young’s modulus within the different layers define how σ₁ is distributed over the entire model. More the contrast between the Young’s moduli of the different layers, more is the contrast in the differential stress distribution within the layers. As the Young’s modulus value of the middle layer approaches the value of the other layers, the whole system acts as a single layer and so there will be no contrast in the differential stress within individual layers.

Similar trend is noticed in the von Mises stress distribution over the three layers; with an increase in von Mises stress within the middle layer and a drop
in von Mises stress within the top and bottom layers as the Young’s modulus is increased. It is also noticed that the absolute value of the von Mises stress within the top and bottom layers is different as seen in Fig 5.3. Same argument about the contrast in Young’s moduli of the layers can be applied to explain this behaviour.

Fig 5.3: von Mises stress distribution in the middle of each layer as a function of Young’s modulus

The principal stresses within the layers are compressive in nature where \( \sigma_y \), which is the direction of the tectonic stress, acts as the maximum principal stress \( \sigma_1 \) in all the layers for values of Young’s modulus below 60 GPa (Fig 5.4.a). As the value of Young’s modulus increases beyond 60 GPa, \( \sigma_y \) still acts as the maximum principal stress \( \sigma_1 \) in the top and middle layers but in the bottom layer, \( \sigma_z \) acts as the maximum principal stress \( \sigma_1 \) (Fig 5.4.b). In all of the scenarios, \( \sigma_x \) acts as the minimum principal stress \( \sigma_3 \) in each of the layers. Due to this change, there is a slight deviation from the regular trend in the differential stress distribution within the bottom layer when \( \sigma_z \) replaces \( \sigma_y \) as the maximum principal stress. However, von Mises stress does not show any deviation from the regular trend as it takes all the principal stresses into account and does not depend on the change of position of the principal stresses.

Fig 5.4: Schematic representation of the orientation of the first and second principal stresses in the bottom layer when the value of Young’s modulus of the middle layer is a) less than 60 GPa and b) more than 60 GPa
5.1.2 Variation of Poisson’s ratio

The Poisson’s ratio of the middle layer is varied from 0.2 to 0.35 in steps of 0.5 (including 0.27, which is the default value) while the Poisson’s ratios of the top and bottom layers are maintained at the same value (Table 5.2).

Table 5.2: List of relevant modelling parameters used in this scenario (modified from table 4.1 and table 4.2)

<table>
<thead>
<tr>
<th>Modelling parameters</th>
<th>Top layer</th>
<th>Middle layer</th>
<th>Bottom layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (ρ)</td>
<td>2160 kg/m³</td>
<td>2860 kg/m³</td>
<td>2160 kg/m³</td>
</tr>
<tr>
<td>Young’s modulus (E)</td>
<td>30 GPa</td>
<td>50 GPa</td>
<td>30 GPa</td>
</tr>
<tr>
<td>Poisson’s ratio (ν)</td>
<td>0.25</td>
<td>0.2 – 0.35</td>
<td>0.25</td>
</tr>
<tr>
<td>Tectonic stress (σ_H)</td>
<td>80 MPa</td>
<td>80 MPa</td>
<td>80 MPa</td>
</tr>
<tr>
<td>Overburden pressure (σ_V)</td>
<td>60 MPa</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

There is a subtle impact on the differential stress of the middle layer due to this variation. There is a slight drop in the differential stress within the middle layer as the Poisson’s ratio of that layer is increased whereas there is almost no variation in the differential stress within the top and bottom layers, as seen in Fig 5.5.

Fig 5.5: Differential stress distribution in the middle of each layer as a function of Poisson’s ratio

Poisson’s ratio change has an impact on the horizontal stress distribution within the middle layer alone as this parameter is changed only within the middle layer. With an increase in Poisson’s ratio, there is an increase in the horizontal component of the overburden pressure which is constant at 60 MPa. This increase however is slightly less in the y-direction which is the direction of applied tectonic stress when compared to the x-direction on which no external stress is applied. Thus, if the differential stress is calculated using σ_y and σ_x which act as the principal stresses σ_1 and σ_3 respectively, there is a slight decrease in the differential stress with an increase in Poisson’s ratio.
The von Mises stress distribution also shows subtle effect to the change in Poisson’s ratio. There is a slight drop in the von Mises stress with an increase of Poisson’s ratio within the middle layer but the von Mises stress increases again with further increase in Poisson’s ratio. The effect is more or less negligible, as seen in Fig 5.6. Constant values of von Mises stress are seen within the top and bottom layers but the bottom layer witnesses a slight increase in von Mises stress for a value of 0.35 as the Poisson’s ratio of the middle layer, as seen in Fig 5.6.

![Fig 5.6: von Mises stress distribution in the middle of each layer as a function of Poisson’s ratio](image)

### 5.2 Variation of applied stresses

The second series of experiments is designed to compare the effect of overburden pressure and tectonic stress on the stress distribution within the model. All through these experiments, the model is assumed to be at a depth.

#### 5.2.1 Variation of overburden pressure

The overburden pressure, or depth in general is varied from 40 MPa to 80 MPa in steps of 10 MPa (Table 5.3). In terms of depth, it is assumed to have been varied from around 1.5 km to around 3 km deep. The main idea of these experiments is to understand the impact of different stresses on the layers at depth. To understand the effect of overburden pressure (or depth), the default depth value of 2200 km is considered and experiments are conducted for depths which are around ±700 to 800 m of this value.
Table 5.3: List of relevant modelling parameters used in this scenario (modified from table 4.1 and table 4.2)

<table>
<thead>
<tr>
<th>Modelling parameters</th>
<th>Top layer</th>
<th>Middle layer</th>
<th>Bottom layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (ρ)</td>
<td>2160 kg/m³</td>
<td>2860 kg/m³</td>
<td>2160 kg/m³</td>
</tr>
<tr>
<td>Young’s modulus (E)</td>
<td>30 GPa</td>
<td>50 GPa</td>
<td>30 GPa</td>
</tr>
<tr>
<td>Poisson’s ratio (ν)</td>
<td>0.25</td>
<td>0.27</td>
<td>0.25</td>
</tr>
<tr>
<td>Tectonic stress (σ_H)</td>
<td>80 MPa</td>
<td>80 MPa</td>
<td>80 MPa</td>
</tr>
<tr>
<td>Overburden pressure (σ_V)</td>
<td>40 - 80 MPa</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

In the case of the simulations with applied overburden pressure (σ_V) in the absence of horizontal tectonic stress (σ_H), with an increase in burial, there is an increase in differential stresses within all the layers (Fig 5.7.a). This is due to the increase in difference between increasing horizontal and vertical stresses with depth (Fig 4.3).

At the end of the final load step i.e., in the presence of horizontal tectonic stress (σ_H) along with overburden pressure (σ_V) (Fig 5.1), it is noticed that there is no change in the differential stresses within the three layers even with an increase of depth by 100%. This can probably due to the reason that with an increase in overburden pressure, the horizontal stresses increase in the same proportion and since σ_y and σ_x act as the principal stresses σ_1 and σ_3 respectively, their difference is always a constant. There seems to be a slight increase in differential stress of the bottom layer when the overburden pressure is increased to 80 MPa. This is due to the fact of a substantial increase in the vertical stress, σ_z which acts as the maximum principal stress σ_1 in this case since it is much higher than σ_y (Fig 5.4.b). The trend is shown in Fig 5.7.b.

On the other hand, it is observed that there is a decrease in the von Mises stress at the middle of the central layer whereas a relative increase of von Mises stress is observed in the top and bottom layers as the overburden pressure is increased. The increase of von Mises stress within the bottom layer is much more prominent when compared to the top layer, as seen in Fig 5.8.
5.2.2 Variation of horizontal tectonic stress

A default tectonic stress value of 80 MPa is chosen throughout the study. This is based on stress magnitudes expected at such depths of around 2500 m (Pascal et al., 2001). The horizontally applied tectonic stress (for this sensitivity analysis) on the system of three layers is varied from 60 MPa to 100 MPa in steps of 10 MPa (Table 5.4).

Table 5.4: List of relevant modelling parameters used in this scenario (modified from table 4.1 and table 4.2)

<table>
<thead>
<tr>
<th>Modelling parameters</th>
<th>Top layer</th>
<th>Middle layer</th>
<th>Bottom layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density ($\rho$)</td>
<td>2160 kg/m$^3$</td>
<td>2860 kg/m$^3$</td>
<td>2160 kg/m$^3$</td>
</tr>
<tr>
<td>Young’s modulus (E)</td>
<td>30 GPa</td>
<td>50 GPa</td>
<td>30 GPa</td>
</tr>
<tr>
<td>Poisson’s ratio ($\nu$)</td>
<td>0.25</td>
<td>0.27</td>
<td>0.25</td>
</tr>
<tr>
<td>Tectonic stress ($\sigma_H$)</td>
<td>60 - 100 MPa</td>
<td>60 - 100 MPa</td>
<td>60 - 100 MPa</td>
</tr>
<tr>
<td>Overburden pressure ($\sigma_V$)</td>
<td>60 MPa</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

A substantial increase in differential stress is noticed in all of the three layers with an increase in the applied tectonic stress. There is a slight drop in the differential stress within the bottom layer for a tectonic stress increase from 60 MPa to 70 MPa. This is due to the fact that $\sigma_z$ acts as the maximum principal stress $\sigma_1$ since it is higher than $\sigma_y$. For higher tectonic stresses, the direction of application of horizontal tectonic stress acts as the direction of maximum principal stress for the bottom layer as well. The trend of differential stress distribution as a function of applied tectonic stress is shown in Fig 5.9.
Fig 5.9: Differential stress distribution in the middle of each layer as a function of applied tectonic stress.

The von Mises stress too shows a similar trend when the applied tectonic stress is increased. The increase in von Mises stress is much steeper in the middle layer when compared to the top layer which in turn has a steep increase compared to the bottom layer. This trend can also be seen in Fig 5.10.

Fig 5.10: von Mises stress distribution in the middle of each layer as a function of applied tectonic stress.

Fig 5.11 shows the distribution of von Mises stress over the entire model when the simulation is run with default parameters. The von Mises stress within the top layer is observed to be constant throughout whereas a gradual decrease with depth is seen within the middle layer. Also, a subtle increase in von Mises stress with depth is seen in the bottom layer as well.
5.3 Strain development

The noticeable feature in all of these scenarios is that there is no strain development within the layers in the absence of any discontinuities, except in the case of a Poisson’s ratio value of 0.2 for the middle layer. A small value of Plastic Strain Intensity (PSI) is observed in the middle layer when the Poisson’s ratio value is at 0.2 while keeping the rest of the parameters at default (Table 4.1 and Table 4.2). The maximum strain value observed in this case is $5.63 \times 10^{-5}$ which is almost negligible when compared to the strain developed in the rest of the scenarios where fractures are present. The maximum strain values observed in those simulations is of the order of $1 \times 10^{-3}$ as will be seen in the subsequent sections.
6. Modelling results

The results of the modelling, based on the specified modelling strategies are outlined in this chapter. After having dealt with the sensitivity analysis using a simple model without any fractures, the focus is now shifted to the actual study dealing with one fractured layer.

6.1 Single fracture

In the case of a single fracture in the middle layer, the effect of friction coefficient between the fracture surfaces in combination with the fracture orientation($\alpha$). Apart from analysing the stress distribution at the fracture tips and the displacement along the fracture plane, the effect over the entire model is also analysed. Later on, the effect of fracture length is also investigated. This analysis is done by fixing the friction coefficient between the fracture surfaces and also choosing a fixed value for $\alpha$.

6.1.1 Displacement

The friction coefficient and the value of $\alpha$ is varied to investigate the sliding displacement between the contact surfaces. The angle is varied from $10^0$ to $80^0$ in steps of $10^0$. Four friction coefficient values are chosen for each of these angle variations. A fixed fracture length of 4000 m is chosen for each of these simulations (Table 6.1).

Table 6.1: List of relevant modelling parameters used in this scenario (modified from table 4.1 and table 4.2)

<table>
<thead>
<tr>
<th>Modelling parameters</th>
<th>Top layer</th>
<th>Middle layer</th>
<th>Bottom layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orientation ($\alpha$)</td>
<td>-</td>
<td>$10^0$ – $80^0$</td>
<td>-</td>
</tr>
<tr>
<td>Fracture length (l)</td>
<td>-</td>
<td>4000 m</td>
<td>-</td>
</tr>
<tr>
<td>Friction coefficient ($\mu$)</td>
<td>-</td>
<td>0 - 1</td>
<td>-</td>
</tr>
<tr>
<td>Tectonic stress ($\sigma_H$)</td>
<td>80 MPa</td>
<td>80 MPa</td>
<td>80 MPa</td>
</tr>
<tr>
<td>Overburden pressure ($\sigma_V$)</td>
<td>60 MPa</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Fig 6.1 shows the effect of the above mentioned parameters on the contact sliding displacement. It is evident that the maximum displacement for each of the scenarios is seen for an angle of around $40^0$ to $50^0$. Also, with an increase in friction coefficient, the overall displacement between the fracture surfaces is reduced. Friction coefficient in a way decides the sliding between fracture surfaces. So a higher friction coefficient means a higher resistance to sliding and thus the displacement between the surfaces is less when compared to the displacement in a low friction coefficient scenario.
The effect of fracture length on the contact sliding displacement is also investigated. For this scenario, the coefficient of friction is maintained constant at 0.3 and the value of $\alpha$ is fixed at 40°. The fracture length is then varied from 1000 m to 4000 m in steps of 1000 m (Table 6.2).

Table 6.2: List of relevant modelling parameters used in this scenario (modified from table 4.1 and table 4.2)

<table>
<thead>
<tr>
<th>Modelling parameters</th>
<th>Top layer</th>
<th>Middle layer</th>
<th>Bottom layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orientation ($\alpha$)</td>
<td>-</td>
<td>40°</td>
<td>-</td>
</tr>
<tr>
<td>Fracture length (l)</td>
<td>-</td>
<td>1000 - 4000 m</td>
<td>-</td>
</tr>
<tr>
<td>Friction coefficient ($\mu$)</td>
<td>-</td>
<td>0.3</td>
<td>-</td>
</tr>
<tr>
<td>Tectonic stress ($\sigma_H$)</td>
<td>80 MPa</td>
<td>80 MPa</td>
<td>80 MPa</td>
</tr>
<tr>
<td>Overburden pressure ($\sigma_V$)</td>
<td>60 MPa</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Fig 6.2 shows the effect of fracture length on the contact displacement. Larger fractures mean larger surface area between the fractures and this can be the reason why the displacement between the surfaces is high. However, at a certain fracture length, further increase in length will not lead to substantial increase in displacement.
Fig 6.2: Variation in displacement along the fracture surfaces as a function of fracture length for $\alpha = 40^\circ$ and for a friction coefficient (fric) value of 0.3.

Fig 6.3 shows the distribution of contact sliding displacement over the fracture surface for a fracture length of 4000 m, coefficient of friction of 0.3 and for $\alpha = 40^\circ$. It is evident that the maximum displacement is towards the centre of the fracture surface whereas the displacement decreases both vertically and horizontally along the fracture surface.

6.1.2 Plastic Strain Intensity

In the same manner as the above simulations, Plastic Strain Intensity (PSI) as a function of the friction coefficient and the angle between fracture surface and
applied tectonic stress is investigated. PSI values in each of these simulations are measured at the fracture tips as those are the only positions where the strain development is observed. PSI values are measured at the fracture tips in all of the experiments. In this scenario too, a fixed fracture length of 4000 m is chosen (Table 6.1). Fig 6.4 shows that there is an overall reduction in the PSI as the friction coefficient is increased. It is also noticed that the straining happens only for the angles of 40° to 70°. PSI is an indirect translation of the sliding between the fracture surfaces. So a similar trend as the displacement is observed for a constant fracture length.

Fig 6.4: Variation in plastic strain intensity at fracture tips as a function of orientation (α) for different coefficient of friction (fric) values

The effect of fracture length on the Plastic Strain Intensity is also investigated. This is done by fixing the coefficient of friction value at 0.3 and maintaining a constant value of α = 40°. The fracture length is varied from 1000 m to 4000 m in steps of 1000 m (Table 6.2). Fig 6.5 shows the effect.

Fig 6.5: Variation in plastic strain intensity at fracture tips as a function of fracture length for α = 40° and for a friction coefficient (fric) value of 0.3
It is already observed that the maximum displacement is at the middle of the fracture surface and it decreases both laterally and vertically along the surface (Fig 6.3).

Fig 6.6 shows the development of Plastic Strain Intensity at the fracture tips when the simulation is run with default parameters with a coefficient of friction of 0.3 and $\alpha = 40^0$.

6.1.3 Stress at fracture tips

The principal stress $\sigma_3$ at the fracture tips attains a minimum value. This stress value at the fracture tips is investigated as a function of friction coefficient and also as a function of the angle between the fracture surface and the applied tectonic stress. Fracture length used in these simulations is 4000 m (Table 6.1). Fig 6.7 shows the result. It is noticed that the tensile stresses develop for angles greater than $20^0$ for a friction coefficient of 0 and this cut-off angle increases with the increase of friction coefficient and tensile stresses develop from an angle of $30^0$ in the case of a friction coefficient of 1. Another notable observation is that the maximum tensile stresses are developed for angles around $30^0$ to $40^0$ in each of these cases. Even though a good pattern in this behaviour is not observed, it can be concluded that the tensile stresses at the
fracture tips drop further with an increase of angle beyond $40^0$. This can be related to the findings by Misra et al. (2009) where the normalized tensile stresses are found to be maximum for a specific crack angle depending on the condition and maintains a bell-shaped profile (Fig 3.2.a).

![Graph showing variation of $\sigma_3$ at fracture tips as a function of orientation ($\alpha$) for different coefficient of friction (fric) values.](image)

**Fig 6.7**: Variation of $\sigma_3$ at fracture tips as a function of orientation ($\alpha$) for different coefficient of friction (fric) values

The effect of fracture length on the development of these tensile stresses is also investigated. For this scenario, a constant friction coefficient of 0.3 is considered and $\alpha$ is fixed at $40^0$ (Table 6.2). As it is observed previously, tensile stresses are developed for an angle of $40^0$. The magnitudes of these stresses are different for different fracture lengths as seen in Fig 6.8. This is a slightly different profile compared to the findings of Misra et al. (2009) where there is a constant increase in tensile stress as the fracture length increases (Fig 3.2.b). It can be the case that the magnitude of tensile stress increases till a particular fracture length but with a further increase in fracture length, the magnitude of tensile stress decreases.

![Graph showing variation of $\sigma_3$ at fracture tips as a function of fracture length for $\alpha = 40^0$ and for a friction coefficient (fric) value of 0.3.](image)

**Fig 6.8**: Variation of $\sigma_3$ at fracture tips as a function of fracture length for $\alpha = 40^0$ and for a friction coefficient (fric) value of 0.3
Fig 6.9 shows the distribution of $\sigma_3$ along the middle layer when the simulation is run with default parameters with a coefficient of friction of 0.3 and for $\alpha = 40^0$. It can be clearly seen that the tensile stresses are developed at the tips of the fractures and the compressive stress is gradually evenly distributed along the surface, away from the fracture.

![Image](http://example.com/image.png)

**Fig 6.9**: A screenshot depicting the development of tensile stress ($\sigma_3$ in MPa) at fracture tips when the simulation is run using default parameters (Table 4.1) and for $\alpha = 40^0$.

### 6.1.4 Variation within the other layers

Even though none of the above scenarios involve changing the parameters within the top and bottom layers, it is interesting to look at the effects of the changes in the middle layer over the top and bottom layers. Fig 6.10 and Fig 6.11 show the distribution of differential stress and von Mises stress in the top layer as a function of angle between the fracture surface and the applied tectonic stress for different coefficient of friction values with a fixed fracture length of 4000 m (Table 6.1).
It is observed that there is a decrease in both differential stress and the von Mises stress in the top layer as the coefficient of friction is increased from 0 to 1. Fig 6.12 and Fig 6.13 show the distribution of differential stress and von Mises stress within the bottom layer as a function of fracture orientation (α) for different coefficient of friction values with a fixed fracture length of 4000 m (Table 6.1).
As in the case of the top layer, a decrease in differential stress and von Mises stress can be seen within the bottom layer as well when the coefficient of friction is increased.

Fig 6.14 shows the distribution of differential stress and von Mises stress within the top and bottom layers as a function of fracture length. The differential stresses within the top and bottom layers are observed to have the same magnitude but the von Mises stress in the bottom layer is relatively higher than the von Mises stress in the top layer. In spite of this difference, the trend of stresses within the top and bottom layers is the same with changing fracture length (Table 6.2).
Fig 6.14: Stress distributions in the middle of top and bottom layers as a function of fracture length (DS: Differential Stress; VM: von Mises stress)

Fig 6.15, Fig 6.16 and Fig 6.17 show the map view of the distribution of von Mises stresses within the top, middle and bottom layers. The cross section is taken at the middle of each layer.

Fig 6.15: A screenshot of the map view depicting the distribution of von Mises stress (in MPa) at the middle of the top layer when the simulation is run using default parameters (Table 4.1) and for $\alpha = 40^\circ$
Fig 6.16: A screenshot of the map view depicting the distribution of von Mises stress (in MPa) at the middle of the central layer when the simulation is run using default parameters (Table 4.1) and for $\alpha = 40^\circ$.

Fig 6.17: A screenshot of the map view depicting the distribution of von Mises stress (in MPa) at the middle of the bottom layer when the simulation is run using default parameters (Table 4.1) and for $\alpha = 40^\circ$. 

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44
6.2 Two parallel fractures

In this study, the effect of spacing between the two fractures and also the overlap/underlap between the two fractures is analysed. For this scenario, a fixed friction coefficient value of 0.3 and also a fixed value of $40^\circ$ for $\alpha$.

6.2.1 Displacement

For the first set of simulations, a fixed fracture length of 4000 m is chosen for each of the parallel fractures. As in the previous scenarios with a single fracture, the contact sliding distance is investigated.

Table 6.3: List of relevant modelling parameters used in this scenario (modified from table 4.1 and table 4.2)

<table>
<thead>
<tr>
<th>Modelling parameters</th>
<th>Top layer</th>
<th>Middle layer</th>
<th>Bottom layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orientation ($\alpha$)</td>
<td>-</td>
<td>$40^\circ$</td>
<td>-</td>
</tr>
<tr>
<td>Fracture length (l)</td>
<td>-</td>
<td>4000 m</td>
<td>-</td>
</tr>
<tr>
<td>Friction coefficient ($\mu$)</td>
<td>-</td>
<td>0.3</td>
<td>-</td>
</tr>
<tr>
<td>Tectonic stress ($\sigma_H$)</td>
<td>80 MPa</td>
<td>80 MPa</td>
<td>80 MPa</td>
</tr>
<tr>
<td>Overburden pressure ($\sigma_V$)</td>
<td>60 MPa</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Fracture spacing</td>
<td>-</td>
<td>100 – 1500 m</td>
<td>-</td>
</tr>
<tr>
<td>Fracture overlap/underlap</td>
<td>-</td>
<td>4000 m</td>
<td>-</td>
</tr>
</tbody>
</table>

Fig 6.18 shows the variation of the displacement as a function of spacing between the two parallel fractures. Simulations are run with variation of fracture spacing from 100 m to 1500 m (Table 6.3). Data is collected from both the fractures and since the displacement values are more or less the same with less than 0.1% difference, the analysis is done with displacement values of only one fracture surface.
It is observed that till a certain spacing, 500 meters in this case, there is a steep impact of the second fracture in the vicinity, beyond which, there is a subtle impact of the second fracture.

For the second set of simulations, fracture lengths of 2000 m are chosen along with a constant friction of coefficient value of 0.3 and a fixed value of $40^\circ$ for $\alpha$ (Table 6.4). Fracture overlap values are chosen from 0 m to 2000 m and also an underlap value of 500 m is chosen between the tips of both the fractures.

Table 6.4: List of relevant modelling parameters used in this scenario (modified from table 4.1 and table 4.2)

<table>
<thead>
<tr>
<th>Modelling parameters</th>
<th>Top layer</th>
<th>Middle layer</th>
<th>Bottom layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orientation ($\alpha$)</td>
<td>-</td>
<td>40$^\circ$</td>
<td>-</td>
</tr>
<tr>
<td>Fracture length (l)</td>
<td>-</td>
<td>2000 m</td>
<td>-</td>
</tr>
<tr>
<td>Friction coefficient ($\mu$)</td>
<td>-</td>
<td>0.3</td>
<td>-</td>
</tr>
<tr>
<td>Tectonic stress ($\sigma_H$)</td>
<td>80 MPa</td>
<td>80 MPa</td>
<td>80 MPa</td>
</tr>
<tr>
<td>Overburden pressure ($\sigma_V$)</td>
<td>60 MPa</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Fracture spacing</td>
<td>-</td>
<td>500 m</td>
<td>-</td>
</tr>
<tr>
<td>Fracture overlap/underlap</td>
<td>-</td>
<td>-500 - 2000 m</td>
<td>-</td>
</tr>
</tbody>
</table>

Fig 6.19 shows the influence of fracture overlap on the contact sliding displacement.

It is observed that the displacement gradually decreases as the overlap between the two fractures is increased. Except in the case of an overlap of 500 m and 1000 m, where similar displacement values are observed, the above mentioned trend exists. Fig 6.20 shows the displacement along the parallel fracture surfaces when the simulation is run for fracture lengths of 4000 m and spacing between the fractures is 500 m. As in the case of a single fracture, the displacement is highest at the centre and it decreases along the fracture surface, both horizontally and vertically.
6.2.2 Plastic Strain Intensity

Strain starts to develop at the fracture tips like in the case of a single fracture. The intensity of strain development is also dependant on the fracture spacing and the overlap/underlap between the two fractures. Fig 6.21 shows the variation of Plastic Strain Intensity (PSI) as a function of fracture spacing. Simulations are run with constant fracture lengths of 4000 m while fixing the coefficient of friction value as 0.3 and also for a fixed value of α (Table 6.3).

It is observed that with an increase of spacing from 100 m to 250 m, there is a drop in PSI but with further increase in spacing, a trend with an overall increase in PSI is observed.
The second set of simulations are run by fixing the fracture lengths at 2000 m along with a constant coefficient of friction value of 0.3 and a constant value for $\alpha$. The overlap between the two fractures is changed from 0 m to 2000 m while an undelap situation is also considered where the fracture tips are separated by 500 m (Table 6.4). Fig 6.22 shows the variation of PSI as a function of fracture overlap.

![Graph showing the variation of PSI with fracture overlap.](image)

**Fig 6.22:** Variation of plastic strain intensity as a function of fracture overlap for $\alpha = 40^\circ$, friction coefficient (fric) of 0.3 and length of each fracture = 2000 m

It is observed that as the overlap increases from -500 m to 500 m, there is an increase in PSI and a further increase of fracture overlap decreases the value of PSI. Fig 6.23 shows the development of strain at the fracture tips in a default case when the fracture lengths are 4000 m each and the spacing between them is 500 m.
Fig 6.23: A screenshot depicting the plastic strain intensity development at fracture tips when the simulation is run using default parameters (Table 4.1) and for $\alpha = 40^0$.

### 6.2.3 Stress at fracture tips

Similar to the case with a single fracture, tensile stresses are developed at the fracture tips when the coefficient of friction is 0.3 and the value of $\alpha$ is $40^0$ (Table 6.3). As in the previous two cases, the first set of simulations investigate the effect of fracture spacing on the magnitude of the tensile stress at the fracture tips, as seen in Fig 6.24.

Fig 6.24: Variation of $\sigma_3$ at fracture tips as a function of fracture spacing for $\alpha = 40^0$, friction coefficient (fric) of 0.3 and length of each fracture = 4000 m.
The second set of simulations is to investigate the effect of fracture overlap/underlap (Table 6.4) on the magnitude of tensile stress at the fracture tips and the results are shown in Fig 6.25.

Fig 6.25: Variation of $\sigma_3$ at fracture tips as a function of fracture overlap for $\alpha = 40^\circ$, friction coefficient (fric) of 0.3 and length of each fracture = 2000 m

Fig 6.26 shows the distribution of $\sigma_3$ at the centre of the middle layer. It can be clearly observed that the least values of stress are developed at the fracture tips.

Fig 6.26: A screenshot depicting the least $\sigma_3$ (in MPa) development at fracture tips when the simulation is run using default parameters (Table 4.1) and for $\alpha = 40^\circ$
6.2.4 Stress between the fractures

So far we have been looking at the changes happening at fracture tips but one of our initial questions is also about changes between the fractures. From the previous simulations, it is already evident that the PSI between the fractures is zero (Fig 6.23). Differential stress and von Mises stress values are measured at the centre of the middle layer i.e., in between the fractures. Fig 6.27 shows the variation of differential stress and von Mises stress at the middle of central layer when the spacing between fractures is changed.

![Fig 6.27](image1.png)

**Fig 6.27**: Stress values at the middle of the central layer as a function of fracture spacing. DS: Differential Stress, VMS: von Mises Stress

Fig 6.28 shows the variation of differential stress and von Mises stress at the middle of central layer when the overlap between the two fractures is changed.

![Fig 6.28](image2.png)

**Fig 6.28**: Stress values at the middle of the central layer as a function of fracture overlap. DS: Differential Stress, VMS: von Mises Stress
It is therefore clear that not only stress/strain localization at fracture tips is influenced by these parameters but the region between the fractures too is affected by the interaction between the fractures. Even though the strain and tensile stresses are localized at fracture tips (Fig 6.23 and Fig 6.26), the differential stress and von Mises stress in between the fractures is influenced by the interaction between the two fractures. Only for small fracture spacing (<250 m), the differential stress and von Mises stress see a decrease in their magnitude with an increase in fracture spacing. In general, with a decrease in fracture interaction; either by increasing spacing or by decreasing fracture overlap; the magnitude of differential stress and von Mises stress between the fractures increases.

6.2.5 Variation within the other layers

The effect of fracture spacing and fracture overlap on the stress distribution within the top and bottom layers is also investigated simultaneously. Fig 6.29 and Fig 6.30 show the effect of fracture spacing on the differential stress and von Mises stress of the top and bottom layers.

![Graph showing variation in differential stress at the middle of top and bottom layers as a function of fracture spacing for parameters as in Table 6.3](image-url)
A steep decrease in the stresses is seen as the spacing is increased but the stresses are gradually constant as the fracture spacing is further increased. Fig 6.31 and Fig 6.32 show the effect of fracture overlap/underlap on the differential and von Mises stresses of the top and bottom layers.
Fig 6.32: Variation in von Mises stress at the middle of top and bottom layers as a function of fracture overlap for parameters as in Table 6.4

Though the differential stresses within the top and bottom layers have the same magnitude with change in fracture overlap, the von Mises stresses in these layers have different magnitudes as the fracture overlap changes.

Fig 6.33, Fig 6.34 and Fig 6.35 show the map view of the distribution of von Mises stresses within the top, middle and bottom layers. The particular scenario is for the case when the fracture lengths are 4000 m each and the spacing between the fractures is 500 m. The cross section is taken at the middle of each layer.

Fig 6.33: A screenshot of the map view depicting the distribution of von Mises stress (in MPa) at the middle of the top layer when the simulation is run using default parameters (Table 4.1) and for $\alpha = 40^\circ$
Fig 6.34: A screenshot of the map view depicting the distribution of von Mises stress (in MPa) at the middle of the central layer when the simulation is run using default parameters (Table 4.1) and for $\alpha = 40^\circ$.

Fig 6.35: A screenshot of the map view depicting the distribution of von Mises stress (in MPa) at the middle of the bottom layer when the simulation is run using default parameters (Table 4.1) and for $\alpha = 40^\circ$. 

55
6.3 Realistic fracture distribution

After investigating the impact of the various parameters on the tectonic model, in the final analysis, a more realistic fracture distribution scenario is chosen. A set of 16 fractures are taken from a case study from Jordan, by G. Strijker (Strijker et al., submitted). These fractures have random distribution in space and with an assumption that the fractures are vertical and have the same height. These fractures not only have different spacing, overlap and lengths but also are not parallel to each other. In this case study, a comparison is made between a single-layered model in which the model comprises of only one layer in which the fractures are present; and a three-layered model in which the layer containing the fractures is sandwiched by layers on top and bottom, as in the previous studies. Default values for the mechanical parameters are chosen along with the applied stress magnitudes. Friction coefficient value for all the fracture surfaces is chosen to be 0.3 and the value of α is $40^\circ$ (Table 6.5).

Table 6.5: List of relevant modelling parameters used in this scenario (modified from table 4.1 and table 4.2)

<table>
<thead>
<tr>
<th>Modelling parameters</th>
<th>Top layer</th>
<th>Middle layer</th>
<th>Bottom layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orientation (α)</td>
<td>-</td>
<td>40°</td>
<td>-</td>
</tr>
<tr>
<td>Friction coefficient (μ)</td>
<td>-</td>
<td>0.3</td>
<td>-</td>
</tr>
<tr>
<td>Tectonic stress (σ_H)</td>
<td>80 MPa</td>
<td>80 MPa</td>
<td>80 MPa</td>
</tr>
<tr>
<td>Overburden pressure (σ_V)</td>
<td>60 MPa</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

6.3.1 Displacement

The first noteworthy observation is regarding the displacement along the contact surface. In the case of a single-layered model, the displacement is highest at the middle and it decreases horizontally along the fracture surface, as seen in Fig 6.36.
Fig 6.36: A screenshot depicting the displacement (in meters) along the fracture surfaces in a single layered scenario when the simulation is run using default parameters (Table 6.5).

In the case of a three-layered scenario, the displacement is highest at the middle but it decreases both horizontally and vertically along the fracture surface, as seen in Fig 6.37.
Fig 6.37: A screenshot depicting the displacement (in meters) along the fracture surfaces in a three layered scenario when the simulation is run using default parameters (Table 6.5)

The maximum displacement associated with each of these fractures is plotted for both these scenarios, as seen in Fig 6.38. The fractures are numbered from left to right; 1 being the left-most and 16 being the right-most, with reference to the above figure.

Fig 6.38: Variation of the maximum displacement along the fracture surfaces for each of the 16 fractures, moving from left to right in single layered and a three layered scenarios
It can be clearly observed that even though the magnitude of the highest displacement along the fracture surface is different, there is a common trend in the relative change in magnitude as we move from left to right. This is primarily associated to the influence of the neighbouring fractures on the displacement along a specific fracture surface. This trend in displacement shows that fractures tend to have more influence from the neighbours if the spacing is less and overlap is high. It is also observed that fractures making partial overlap with their neighbours have maximum displacement in the zone which is not overlapping with the neighbouring fracture. This off-centre location of maximum slip is also reported by the study of Willemse et al. (1996) as mentioned in the earlier chapter on previous work.

6.3.2 Stress patterns

Fig 6.39, Fig 6.40 and Fig 6.41 illustrate the distribution of von Mises stress in the middle of top, central and bottom layers. It can be clearly observed that the presence of fractures within the central layer definitely have an impact on the stress distribution within the top and bottom layers as well. Looking at the fractured layer, minimum von Mises stress is concentrated close to the fracture planes and in between the fracture surfaces while maximum stress values are commonly localized at the fracture tips (Fig 6.40). Considering the bottom and top layers, maximum von Mises stress is concentrated in the zone right above/below the fractures and it decreases away from this zone.

Fig 6.39: A screenshot of the map view depicting the distribution of von Mises stress (in MPa) at the middle of the top layer when the simulation is run using default parameters (Table 6.5)
Fig 6.40: A screenshot of the map view depicting the distribution of von Mises stress (in MPa) at the middle of the central layer when the simulation is run using default parameters (Table 6.5)

Fig 6.41: A screenshot of the map view depicting the distribution of von Mises stress (in MPa) at the middle of the bottom layer when the simulation is run using default parameters (Table 6.5)
As observed in the previous scenarios, minimum $\sigma_3$ develops at the fracture tips. Fig 6.42 illustrates the distribution of $\sigma_3$ at a slice taken in the middle of the central layer. In between the fracture surfaces, compressive stresses prevail but as seen in the scenario with two fractures, the magnitude of stress developed between the fractures is influenced by the interaction between the neighbouring fractures.
7. Discussion

The number of oil and gas fields in which fractures are recognized as playing a major role has risen in recent years. A relation to such reservoirs can be made through this study. Incorporating the failure criteria to the stress/strain distributions can help us better understand the development of new discontinuities or the reactivation of existing discontinuities. This will further strengthen our knowledge on the reservoir properties like permeability. Opening-mode fractures may act as highly permeable conduits capable of rapidly transmitting water, oil or gas. Such a robust prediction of the stress distribution in a reservoir is also crucial for optimal design of horizontal well trajectories and multiple fracs in horizontal wells. A combination of geomechanical modelling and fluid flow simulations can be quite valuable to the hydrocarbon reservoir production: early water breakthrough, compartmentalization and dual permeability effects being the well-known ones. Therefore such an analysis can help geologists and engineers to make most effective use of the fracture system in a subsurface reservoir.

It is evident that a lot of assumptions have been made throughout this analysis and there are also a lot of limitations to this kind or as a matter of fact, any numerical analysis technique. The aim of this study though is to make a preliminary prediction on the model behaviour when subjected to the required boundary conditions.

Combining this study with the findings of Misra et al. (2009), the development of shear bands and wing cracks are seen at areas with strain localization which is also concentrated at fracture tips. Strain intensities are the highest at fracture tips but gradually decreases away from the tip. Even though the stress distribution between the fractures is highly dependent on the interaction between the neighbouring fractures, it is the strain development that is more important in predicting the intensity of deformation that initiates at fracture tips. Therefore, the displacement along the fracture surface, which also has a similar trend as the PSI, can be one of the indicators for the intensity of deformation. Finite element models like these can help us with such predictions.

Since one of our questions initially is to look at the stress/strain distributions within the other layers, the study shows that the changes within the central layer do have an impact on the stress distribution within the overlying and/or underlying layers too. But since strain distribution is more important for predicting deformation, the presence of any kind of discontinuity within the other layers can initiate deformation patterns within them. So for such an analysis, it is always important to have realistic modelling parameters and rheological properties for each of the layers even though we are concerned with the changes within one layer alone.

In spite of the robustness of this approach, some of the noteworthy points for discussion can be:
(i) If such a continuous layering can actually exist in reality; especially at such a large scale.
(ii) If the applied stresses on a system are actually as systematic and in order as they have been looked at in this analysis.
(iii) If the reaction to applied stresses would be the same even in the presence of pore-fluids like hydrocarbons or water.
(iv) If in reality, the fractures are vertical and extend throughout the particular layer of interest.

By nature, several of the input parameters for a geomechanical reservoir model, like magnitude and orientation of the paleo-stress fields and past mechanical rock properties are usually poorly constrained. Points like these of course give rise to a lot of discussion on the credibility of such an analysis but one has to realize that finite element method in itself makes a lot of assumptions but it tries to give a close match to the reality. It is therefore very important for us to prioritize the key points of interest of the analysis and back the results with experimental or field evidences that can help us to further strengthen these results.
8. Conclusions and recommendations

Geomechanical models provide a valuable tool for a prognosis of tectonic stresses and fracture networks. Such a robust prediction of the stress distribution is very crucial for understanding the failure patterns. From this study, it can therefore be concluded that:

- Mechanical property contrast between the layers, especially the Young’s modulus has a strong impact on the distribution of stress within the layers.

- In a scenario where overburden pressure and tectonic stress coexist; the tectonic stress magnitude governs the stress distribution to a larger extent when compared to the overburden pressure magnitude.

- Fracture length and fracture orientation ($\alpha$) not only govern the stress and strain distribution within the fractured layer, but also have an impact on the stress distribution within the surrounding layers. Friction coefficient too plays a small but vital role. Fracture displacement increases with an increase in fracture length. Differential and von Mises stresses in the top and bottom layers too increase till the fracture length reaches 3000 m and then they undergo a subtle decrease. Displacement and Plastic Strain Intensity (PSI) peak at orientation of about $40^\circ$ – $50^\circ$ for a specific friction coefficient and the peak value decreases with an increase in friction coefficient.

- In the case of a two fracture configuration, the spacing between the fractures and the overlap/underlap between the fractures play a role in the stress/strain distribution over the entire model. Not only at the fracture tips but also in between the fractures, these parameters govern the stress distribution. Fracture displacement increases with an increase in fracture spacing while it decreases with an increase in fracture overlap. Differential and von Mises stresses in the middle of top and bottom layers decrease with fracture spacing till a spacing of 1000 m and further increase in spacing does not change these stress magnitudes. These stresses in the top and bottom layers peak for a fracture overlap of 0 m but drop consistently with an increase in overlap/underlap. If we talk about the impact on the middle of the central layer, these stresses increase with an increase in fracture spacing from 250 m onwards. Increase in fracture overlap on the other hand sees a drop in these stresses in the middle of central layer. So it can be implied that increase in interaction between the neighbouring fractures will decrease the differential and von Mises stresses in the region between the fractures. But for the initiation of fracture propagation, strain developed at fracture tips is more relevant, especially when we look at the patterns of development of wing cracks and shear bands (Misra et al., 2009).

- Differences do exist between a single layered model and a three layered model. Primary difference exists in the displacement along the fracture surface; both show high displacement at the centre of the surface and a reduction in
displacement towards the edge of the fracture surface. The primary difference being the displacement reducing both laterally and vertically in the case of a three layered model while the displacement reduces only laterally. Displacement values are highly influenced by the influence of the neighbouring fractures. It is also observed that the presence of a fractured layer impacts the stress distribution within the surrounding layers.

This study is aimed to understand the effects of different input parameters on the whole model. A lot of assumptions have been made while translating it from the Basal Zechstein lithology. To make it into an actual case study and to apply it to this reservoir, accurate values can be used, which can be derived from mechanical testing. There is scope for a lot of improvement but this study for sure can be used to fill our gaps in understanding the effects of compressive stresses on a three layered model with a single fractured layer. Application to well-documented case studies will help us to compare model predictions and field observations and provide us with means to improve modelling techniques and gain further insights into reservoir geomechanics.
9. References


