Study on Borehole Stability in Fractured Rocks in Deep Drilling Conditions

Ehtesham Karatela, M.Sc (University of Adelaide)

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The University of Adelaide

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Abstract

Wellbore or borehole stability is a serious and expensive problem in mining and petroleum industry. With the development of new exploration and production technologies, Australian miners are looking for mineral deposits in deep seated environments. Borehole instabilities can be encountered at any stage in the life of a well, including drilling, completion and production. Borehole instabilities are the main cause of difficulties encountered during drilling. This results in significant expenditure, excessive loss of time, sometimes it results in loss of borehole.

One of the most integral part of rock formation is the presence of joints and fractures at a small scale. According to some researchers most of the rock formations have fractures at some scale. When boreholes are drilled in such formations, instability is a major concern. In order to accurately predict the behaviour in fractured media, the matrix and fracture deformations as well as fluid flow in fractures need to be fully coupled.

A number of factors influence borehole instabilities in fractured rocks. This may include solid-fluid interaction (rock and chemically active mud), complex stress conditions, probable borehole deviation, heterogeneity in the formation and drilling operations. Vertical boreholes are usually stable where overburden is the maximum stress (σ_1). However, drilling vertically does not guarantee a stable hole. Instability in a borehole is dominated by the in-situ stress system. When an undisturbed rock is penetrated by drill bit, the in-situ stresses are redistributed. As a result, in-situ stresses tend to concentrate around the excavation. This is presented by an increase in stress concentration in the vicinity of the borehole and induced stresses near intersection of discontinuities and fracture tips. These induced stresses can lead to rock failure of the borehole wall.

This thesis represents three journal publications which represent simulation of an unsupported and mud supported vertical borehole in two dimensional and three-dimensional analyses. Because the nature of rock media is considered as fractured with single permeability along discontinuities, Discrete Element Model (DEM) was considered to be the best tool for investigations.

First of all, Numerical investigation on the behaviour of an unsupported vertical cylindrical borehole in heavily fractured rock mass is presented. DEM based code Universal Distinct Element Code (UDEC) is used as the simulation tool. With taking into account the in-situ stress conditions in Cooper basin, South Australia. A borehole of 0.15 m radius in the centre of the model was simulated comprising of two fracture sets. The

vertical stress applied correlates with the 1.5 km depth of the Cooper basin. The effect of fracture orientation and in-situ horizontal stress ratio (σ_H / σ_h) on the stability of the rock mass around the borehole was investigated. It has been shown that the induced stresses due to excavation lead to the development of a yielded zone around the borehole. Borehole stability criteria relevant to the extent of yielded zone and maximum displacement around the borehole were introduced into stability analysis. Results show that when the in-situ stress ratio increases the rock blocks at borehole wall tend to move towards the centre of borehole, consequently yielded zone around the borehole increases. Similarly, the fracture orientation changes the angle of borehole fracture intersection which aids in displacement increase as well as the location of block detachment. Furthermore, the change in fracture orientation highly influences the formation of yielded zone.

Secondly, a 3D discrete element model is presented which is developed to simulate a borehole drilled in fractured rock mass. A model with overbalanced drilling conditions is simulated in this study. In doing so, different depths of a borehole, MB-1 borehole, in Northern Perth basin was simulated. The developed model was validated against log measurements of Caliper log. Rock strength was found to be one of the governing factor in controlling the stability. Thereafter, hydro-mechanical models were generated and it was observed that high mud flow rates and high pore pressure increased the instability around borehole. Furthermore, a parametric study was performed to investigate the influence of viscosity and fluid flow on the stability. Shear displacement linearly increase with an increase in the flow rate while fluid pressure decreases due to the increase in fracture’s aperture with an increase in the flow rate. Similarly, increase in viscosity caused increase in fracture shearing and therefore instability around borehole.

After most important rock mass and operational parameters were analyzed, their influence was determined. A detailed stress analysis of 3D model of Northern Perth basin was carried out. Apart from the regional stress constraints, stress distribution in a small-scale area has several influencers. Constraining these localized stress perturbations is a key element in analyzing borehole stability and related underground excavations. As a final part of this study stress perturbation near the well bore and fracture tips was analyzed. As part of the study a regional model with three major faults was generated which was further used to estimate boundary stresses on descriptive smaller model termed as ‘base model’.

In addition to the magnitude of stresses at tips of discontinuity, it was observed that when stress tensor pass through a material of low stiffness in this case, a discontinuity, it tends to rotate parallel to the discontinuity. A borehole in such rock mass determined that yield zone is in agreement with high stresses along discontinuities. Base model was further subjected to strength anisotropy and stress anisotropy analysis. Effect of stress anisotropy on stress perturbation is found to be very significant whereas strength anisotropy which was studied by changing of friction angle and cohesion in one of the discontinuities slightly affected stress perturbation. In both cases, due to the effect of discontinuities the induced stress field is non-linear.

Statement of originality

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Ehtesham Karatela

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List of Publications

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Chapter 1

Introduction

Mining is one of the most influential and economically stable industries in Australia. Search for commercial minerals dates back for more than three centuries. In earlier days only surface minerals or shallow depth deposits were excavated, but with the advent of new technologies, new exploration methods have been developed that target mineral halos at around 1500 meters and deeper. To explore and estimate the significance of these resources, a borehole is drilled up to the target depth and core samples are extracted from the subsurface. It has since become one of the most efficient method for geotechnical data extraction and analysis. A number of instability issues are encountered during drilling which makes it difficult to penetrate through the rocks and reach the target depth.

Borehole stability is a significant issue in many deep drilling operations in the oil and gas industry. The deformations and breakouts caused by borehole instabilities can have serious consequences that negatively impact reservoir production, resulting in a loss of mud, operational time, substantial expenditures and loss of part of or even the entire borehole. Such failures are costing over $1 billion per year worldwide. Therefore, there is a need to study borehole failure mechanisms to minimise damages and costs as a result of borehole instability.

Borehole instabilities, while drilling operation are the result of several factors. This may include solid-fluid interaction (rock and chemically active mud), complex stress conditions, probable borehole deviation, heterogeneity in the formation and drilling operations. Instability in a borehole is dominated by the in-situ stress system. When an undisturbed rock is penetrated by drill bit, the in-situ stresses are redistributed. As a result, in-situ stresses tend to concentrate around the excavation. This is presented by an increase in tangential stress and decrease in radial stress. These perturbing stresses leads to failure in the direction of maximum horizontal stress (σ_H). The rock overburden removed due to drilling is usually replaced by the mud support. A suitable mud weight is defined as the amount of mud pressure which is greater than the pore pressure of the formation and less than the least principal stress (σ_3). The orientation of rock failure direction is presented earlier is true for isotropic and homogenous rocks. However, predicting a failure in discontinuous medium has not been understood.

Numerous studies on borehole stability have been developed based on linear elastic, elasto-plastic and poro-elastic theory, where the host rocks surrounding the boreholes are assumed to have continuum nature. However, some researchers believe that application of these theories on fractured rocks could lead to misleading results. Therefore, care should be taken when formulating numerical models in which discontinuities are addressed. In case of fractured rocks, failure around borehole wall is an interaction of rock block and fracture properties, in-situ stress and drilling parameters. In natural geologic system, most of the rocks are fractured to some extent. The key to maximize the economic value of such boreholes is to be able to predict if, when and how failure will occur and what precautions can be taken to avoid loss of borehole.

Aadnoy (1988), presented an analytical model to determine the fracture and collapse behaviour of a borehole. He explains that neglecting the influence of heterogeneities in a rock may lead to poor prediction of fracture pressures (Aadnoy 1988). Santarelli et al. (1992), determined that systematic increase in the mud weight which is a common stabilization method; can have a negative impact on stability. Moreover, when drilling fluid invades a fracture, effective stress normal to the fracture plane reduces and has more tendency to slip (Maury 1994; Tan and Chen 2005; Younessi and Rasouli 2010).

Traditionally, borehole stability analysis was established on elasticity or poro-elasticity theory, in which the rocks around the wellbore were considered isotropic. Though, such solutions for naturally fractured rocks may result in incorrect conclusions (Zhang and Roegiers 2000).

Several researchers (Zhang et al., 1999; Chen et al., 2003; Tan and Chen, 2005) presented numerical study for failure in the rocks surrounding a borehole. These authors studied the influence of mud infiltration into the fractures due to high borehole pressures and conclude that flow of fluid in the fractures is highly stress dependant. Several other researchers (Homberg et al., 1997; Gudmundsson, 2000; Bourne and Willemse, 2001; Kattenhorn and Marshall, 2006) explains localized stress concentration at the tips of discontinuities and at the intersection of joint sets.

For the purpose of borehole stability analysis, various numerical methods exist in the literature. These are generally linear elastic (Helstrup et al., 2004). However, in fractured rocks failure analysis of boreholes becomes more complicated because the material is no longer continuous. These methods can be generally divided into continuous based methods and discontinuity based methods.

Finite element model (FEM) is a tool that has been significantly used for borehole stability analysis in continuous rocks. Whereas, several researchers prefer discrete element method (DEM) as an appropriate tool to solve problems regarding borehole instability. Jing and Stephansson (2007) presented several limitations of FEM when modelling discontinuity rock mass.

Salehi et al. (2010) presented a comprehensive numerical study in two Iranian fields. Both fields comprised of fractured carbonates. Authors used a FEM code for wellbore stability analysis. The mesh was validated based on the Kirsch solution for effective stress around the wellbore for a pre-fractured state. A borehole stability criterion based on the size of yielded zone was used to explain the risk of instability. Salehi et al. (2010) concluded that finite element analysis provides ability to predict the integrity of a borehole.

Similarly, Zhang and Roegiers (2000) developed a comprehensive dual porosity and plane strain finite element solution to analyse borehole stability in horizontal wells in naturally fractured rocks. They were able to define a failure criterion based on collapse pressure and spalling off but was unclear to justify the use of finite element model for fractured rocks (Zhang and Roegiers, 2000).

Other researchers (McLean and Addis, 1990; Chen et al., 2001; Chen et al., 2003; Nicolson and Hunt, 2004; Kang et al., 2009; Hu et al., 2012). However, infer that using finite element for the borehole stability analysis of fractured rocks may lead to incorrect solution. Jing (2003) provides a comprehensive analysis on different numerical modelling methodologies and argue that discrete element method (DEM) is the most appropriate method for the numerical analysis of fractured rocks. He explains that in DEM, fractured media is represented as assemblage of blocks connected by discontinuities. The equations of motion for continuous blocks is solved through continuous detection and the contacts are treated separately (L.Jing 2003). Displacement solution in DEM for block rotation, fracture aperture and detachment is simple but not possible in FEM (L.Jing 2003).

In this method, a rock mass is represented as an assemblage of individual components or discrete blocks and joints are defined as interfaces between two distinct bodies (blocks for UDEC and granular particles for PFC). The distinct element method is specifically suitable for modelling problem domains in which the response of the problem domain to a set of boundary conditions is governed by the behaviour of discontinuities intersecting the domain rather than the behaviour of the intact material. The discontinuities divide the domain into a series of distinct blocks that can contact neighbouring blocks or separate from the continuum. The forces and displacement at the contact are calculated through a series of calculations which trace the movement of the blocks (Itasca 2004). Movements result from propagation of the block system resulted due to applied loads. The block propagation is a dynamic process and depends on the physical properties of the discrete system (Jing and Stephansson 2007).

Numerically, the dynamic behaviour is represented by an algorithm in which time step is limited by the assumption that velocity and acceleration of the blocks during propagation is constant within a time step (Camac and Hunt 2004; Itasca 2004). This method is based on the concept that a time step is significantly small to transfer information to its neighbouring elements. Therefore, it corresponds to the fact that there is a finite speed at which information can be transmitted in a physical medium. The calculations of forces and motion of the blocks in the distinct element method are outcome of the application of force-displacement law and newton’s second law of motion. The motion of the individual block is determined by the resultant out of balance force acting on it. UDEC and 3DEC were used to generate models of borehole in this thesis. Details of each code and associated equations is comprehensively explained in the appended papers.

1.1 Research gaps

This thesis focuses on the borehole stability issues in the fractured rocks which occur in deep seated environment. This comprehends that rock mass in question is subjected to significant overburden stress as well as horizontal stresses, which in turn affect fluid flow shearing along discontinuities. Based on the literature review presented herein and in introductory parts of Journal papers presented in this thesis following are the research gaps that have been extracted.

1- Interaction of fractures with in-situ stress has not been exclusively studied using a numerical model. Orientation of fracture in relation to σ_H direction is important to understand because it determines the magnitude of failure along the discontinuity.

Stress regime in subsurface is under equilibrium before drilling. With the drilling bit penetrates into subsurface stresses tend to rearrange themselves and to attain equilibrium concentrate around borehole. Solutions for stress concentration and resulting failure in isotropic homogenous rocks have been well presented in the literature. However, stability of borehole in fractured rock mass is not completely understood.

Few studies can be found in literature which deal with maximum principal stress orientation and the orientation of fracture. Conventionally, in a borehole intersecting fractured rock medium, borehole collapse has been explained by invasion of mud into the fractures. The invasion of mud increases the pore pressure therefore reducing the effective normal stress. A shear release then results in lateral displacement at the fracture plane. However, in underbalanced conditions where mud invasion is unlikely, predominant failure mechanisms are induced by stress concentration. Therefore, it is important to investigate the relative angle between fracture and stress tensors.

Numerical analysis of borehole stability in fractured rocks is generally studied using finite element method. FEM is a wonderful tool for isotropic homogenous rocks, however, for fractured rock mass it may not be the best choice as described in the comprehensive literature review within this thesis. On the other hand, DEM is a preferable choice for rock mechanics problems in fractured rock mass

2- Operational parameters such as mud weight and flow velocity have been investigated in previous studies, however, shear along the discontinuities resulting because of these operational parameters have been missed in regard to borehole stability in discontinuous medium.

A number of experimental and numerical have been used for borehole stability analyses. However, mechanism of borehole failure in fractured rock mass is very complex and has not been completely understood. A pre-drilled fracture is under in-situ stress condition and a specific magnitude of normal stress is applied on the fracture. With the invasion of fluid into the fracture during drilling process, this normal stress is reduced which allows the fracture to slide overcoming the shear force. The shearing along the discontinuities and its effect on borehole stability has not been studied in hydro-mechanical models presented earlier in the literature.

To improve the understanding of the relationship between hydraulic and mechanical processes in fractured rock mass, several studies have used hydro-mechanical modelling of hydraulic field tests combined with fracture displacement measurements. These studies, however, were not extended to borehole stability problems. In general, it is recognized that there is a lack of in-situ data that could help us understand these coupled processes at a smaller scale. In-situ testing of such complex situations has been a major challenge primarily because of technological issues and the cost involved in designing such large-scale project. Numerical methods such as DEM become a very handy tool in such conditions.

3- Localised stress perturbations at fault tips have been widely studied, however, how these perturbations at joint tips and intersection of joint sets react to anisotropic nature of rocks mass has not been extensively studied. Also, how local stress perturbations can affect borehole stability is missing.

Last few decades researchers have carried out intensive research studying and analysing stresses within the earth’s crust. Tingay et al., 2005 and related researchers generated a database of contemporary in-situ stresses under the project world stress map. In their studies researchers explained a number of factors affecting orientation of stress tensors and magnitude of stress at a particular point of depth. With the effect of regional geological structures influencing in-situ stresses, there are some local features in a constrained environment that affect magnitude and orientation of stress. Local geological features such as fractures and related discontinuities also influence stress in a specified area. These local perturbations are very important in determining a wellbore stability model. Because of these perturbations rocks surrounding a discontinuity tend to fail easily. Therefore, potential effect of induced stresses is very important.

In the literature, there are very few studies which predict induced stresses around discontinuities. These studies are primarily concerned with measurement of induced stresses and related change in permeability of subsurface fluid. No studies were found to relate induced stresses because of local geological structures to the borehole stability in discontinuous medium.

1.2 Aims

The overall aim in this dissertation is to present DEM numerical model for borehole stability that couple's mechanical behaviour of rock and fluid flow to simulate naturally fractured rocks. Specifically, there are three main aims as specified below:

1- Present a two-dimensional plane strain solution of discontinuous rock with a central borehole to determine interaction of fracture orientation in regards with σ_H direction and analyse the model in high stress conditions.

To achieve this aim, a two-dimensional DEM model was simulated using UDEC under plane strain conditions. Two fracture sets perpendicular to each other and a central borehole parallel to z-axis (out of the plane) were incorporated in the model. Maximum horizontal and minimum horizontal stresses were oriented parallel to x-axis and y-axis respectfully. Vertical stress is oriented along the z-axis therefore; a vertical borehole is assumed in the model. Magnitudes of In-situ stress data from Cooper basin was extracted from literature and the intact rock mass represented synthetic shale.

A borehole stability criterion based on yield zone and maximum displacement was formulated using monitoring points around the borehole. Once the material and fracture properties are added, a stress boundary is applied. Before a simulation can be processed initial state of equilibrium is achieved under in-situ stresses and zero pore pressure. The model is now simulated to attain equilibrium until stress boundary conditions are satisfied.

To simulate the borehole response; the borehole is first excavated by removing blocks and iteration is continued until equilibrium. This results in changing displacements of the blocks where the effective stress increases the threshold. Displacement of blocks is measured and zone of deformation is marked for analysis (Paper 1).

2- A parametric study of in-situ stress ratio and fracture orientation was carried out in this study. The yield zone and displacement around borehole increased with the increase in stress ratio, thus increasing the instability. Fracture orientation had very different results. Displacement magnitude increased when the fracture angle was increase between 15° - 60°, however it decreased when orientation of fracture was between 60° to 90°. This aim is covered with paper 1. Present a hydro-mechanical coupled model to determine effect of fluid properties on the deformation around the borehole and shear displacement along discontinuities in elastoplastic media.

Two of the most important operational parameters while drilling a well is the mud flow rate and viscosity. In this study, a 3D discrete element model is developed to simulate a borehole drilled in fractured rock mass. A model with overbalanced drilling conditions is simulated in this study. In doing so, different parts of a borehole, MB-1 borehole, in Northern Perth basin was simulated. The developed model was validated against log measurements of Caliper log and strength of rock is found as a governing factor in controlling the stability. Then, hydro mechanical modelling was carried out and it was observed that high mud flow rates and high pore pressure increased the instability around borehole. Furthermore, a parametric study was performed to investigate the influence of viscosity and fluid flow on the stability. Shear displacement linearly increase with an increase in flow rate while fluid pressure is decreases due to increase in fractures aperture with an increase in flow rate. Similarly, increase in viscosity caused increase in fracture shearing and therefore instability around borehole (Paper 2).

In this study, discrete element modelling approach is used to investigate borehole stability and simulate pore pressure generated in rock mass due to presence of underground water and effect of mud pressure on borehole stability. In doing so, a vertical borehole drilled in a rock mass with explicitly defined discontinuities in Perth basin was modelled. Firstly, a layered model of Mountain Bridge (MB-1) borehole is generated and then the yield zone around the borehole is validated against caliper log measurements. Since Caryngina formation in the northern Perth basin is considered to be one of the most prolific shale gas target, subsequently parameters that may affect stability in this region are evaluated. Therefore, by undertaking sensitivity study, influence of fluid flow rate in the borehole and fluid viscosity on borehole stability is investigated at monitoring points around the borehole. Paper 2 describes the modelling works which were done to fulfil this aim.

3- To investigate effect of large-scale structures and discontinuities on in-situ stress generation in a regional and a localized model. Additionally, to investigate the effects of stress and strength anisotropy on in-situ stress perturbation.

local geological features affect stress perturbation in terms of magnitude and orientation of stress at local level which may be contrary to the regional stress. The altered stress state is responsible for the formation of borehole breakout which is basically shear failure zones along the borehole wall in the direction of maximum horizontal stress (σ_H) and can be reoriented because of discontinuities. Therefore, it is important to investigate the interaction of stresses and fracture properties to understand the stability of wellbores. A regional model of a part of Northern Perth (NP) basin is carried out using a DEM based code 3DEC. Several assumptions presented in chapter 4 were applied to generate a simple regional model with three major faults. More detailed model with two fracture sets termed as ‘base model’ was generated in the centre and was subjected to detailed analysis. The purpose of the regional model is to estimate traction on the boundaries of base model. Stress perturbation in base model was estimated and it was observed that relative zones of compression and extension for at the intersection of discontinuities and a stress drop is observed at the single discontinuity. The amount of induced stresses and orientation of principal stress is presented. Furthermore, Strength anisotropy and stress anisotropy is investigated. These analyses showed that however stress perturbation is affected in both cases, the induced stress field is not linear (Paper 3).

1.3 Concluding Remarks

This study provides a systematic approach to understand the issue of borehole stability. It analyses rock mass and operational parameters and in-situ stress in a DEM model and explains their influence on borehole stability. Following conclusions can be drawn from this thesis. Firstly, a two-dimensional study is carried out. Two borehole stability criteria on the basis of maximum displacement and normalized yielded zone were used in this study to evaluate borehole failure mechanism in different modelling conditions. It was observed that stresses concentrated around the borehole. Because of presence of discontinuities induced stresses tend to increase the tangential stress that exceeds the strength of fractured formation which leads the borehole wall to collapse.

In-situ stress ratios were found to be very critical in increasing the deformation and displacement around the borehole. High difference in in-situ stress ratio is observed to be directly proportional to the displacement around borehole. Isotropic stress conditions were also modelled. However, isotrpic stress condition was found to be most stable. Furthermore, anisotropic stress ratio (σ_H/σ_h=2) is observed to be highly unstable. However, such a condition is not very common in the subsurface. On the other hand, anisotropic stress ratio (σ_H/σ_h=1.5) is found to be critical for borehole stability analysis. Rotation of fracture in relation to principal stress orientation also affects borehole stability. Generally, if a discontinuity is parallel to principal stress displacement at borehole wall is minimal. Similarly, if the angle between principal stress and fracture is up to 60°, then the deterioration at the bore wall is very high.

In this thesis, hydro-mechanical models of Northern Perth basin were generated. These DEM simulations are aimed at understanding geomechanical influence on borehole stability in naturally fractured rocks. To simplify the problem domain only MB-1 was modelled. Mudflow rate, pore pressure and viscosity had a very prominent impact of the tensile and shear failure along discontinuities.

Simulation results shows that borehole stability largely depends on the rock strength. These simulations were then compared to caliper log. Hydro-mechanical model termed as ‘base case’ seems to be following the same trend as ‘measurement’ which is the deformation extracted from caliper log. Simulations show very good match with field measurement with minor discrepancies.

Three basic cases termed as HMLP (High mud low pore pressure), HPLM (High pore pressure low mud) and EQMP (equal mud and pore pressure) were simulated after the validation. In HMLP model, large amount of shear displacement was observed and yielded zone around the borehole was significant. For the case of HPLM high pore pressure was applied to the borehole to simulate depletion or production phase. Shear displacement increased when the pore pressure was increased significantly compare to mud pressure. Borehole conditions were balanced only when the pore pressure and mud support (EQMP) was equalized which is an ideal situation but unfortunately it rarely exists.

Furthermore, a sensitivity study, the effect of mud flow rate, and fluid viscosity on the borehole stability was evaluated. These results were expected as higher flow rate translate into higher injection pressures and more energy available for rock failure near the borehole. Furthermore, the results suggested shear failure around the borehole increases with an increase in flow rate. The amount of tensile and shear failure generated as a result of fluid injection showed a very distinct response to changes in fluid viscosity. In the case where low viscosity fluid ($\mu = 1$ cP) was injected, the amount of area failing was lower than the cases with high viscosity fluid ($\mu > 100$ cP). As a result of this, fluid pressure around the borehole decreases with an increase in viscosity, due to the pore-pressure being dissipated with aid of movement of fractures around the borehole.

Stress distribution in a small-scale area has several influencers apart from the tectonic elements. This local stress distribution exists because of small scale geological features which may have a significant influence on the stability of underground excavation. Constraining these localized stress perturbations is a key element in analyzing borehole stability and related underground excavations. As a final part of this study influence of stresses concentrating near the well bore and fracture tips was analysed. It was fond that two zones of compression and extension are formed near the fracture tips. These induced stresses can play a vital role in rock failure in that stress envelope. As part of the study a regional model with three major faults was generated which was further used to estimate boundary stresses on descriptive smaller model termed as ‘base model’.

Stress perturbations in the base model are presented. σ_1 and σ_3 were extracted along the scanline and a marked deflection at joint set intersection was observed. Also stress drop at the discontinuity was observed. In addition to the magnitude of stresses at tips of discontinuity, it was observed that when stress tensor pass through a material of low stiffness in this case, a discontinuity, it tends to rotate parallel to the discontinuity. A borehole in such rock mass determined that yield zone is in agreement with high stresses along discontinuities. Base model was further subjected to strength anisotropy and stress anisotropy analysis. Effect of stress anisotropy on stress perturbation is found to be very significant whereas strength anisotropy which was studied by changing of friction angle and cohesion in one of the discontinuities slightly affected stress perturbation. In both cases, due to the effect of discontinuities the induced stress field is non-linear

Statement of Authorship

Statement of Authorship

Title of Paper	Study on effect of in-situ stress ratio and discontinuities orientation on borehole stability in heavily fractured rocks using discrete element method
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Principal Author

Name of Principal Author (Candidate)	Ehtesham Karatela		
Contribution to the Paper	Overall presentation and structure of the study		
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Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
Signature		Date	26/10/2017

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);
ii. permission is granted for the candidate in include the publication in the thesis; and
iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

Name of Co-Author	Abbas Taheri		
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Name of Co-Author	Chaoshui Xu		
Contribution to the Paper	Help with the code and review.		
Signature		Date	26/10/2017

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Contribution to the Paper	Overall review and input of industrial point of view.		
Signature		Date	21/11/2017

Chapter 2

Paper 1: Study on effect of in-situ stress ratio and discontinuities orientation on borehole stability in heavily fractured rocks using discrete element method

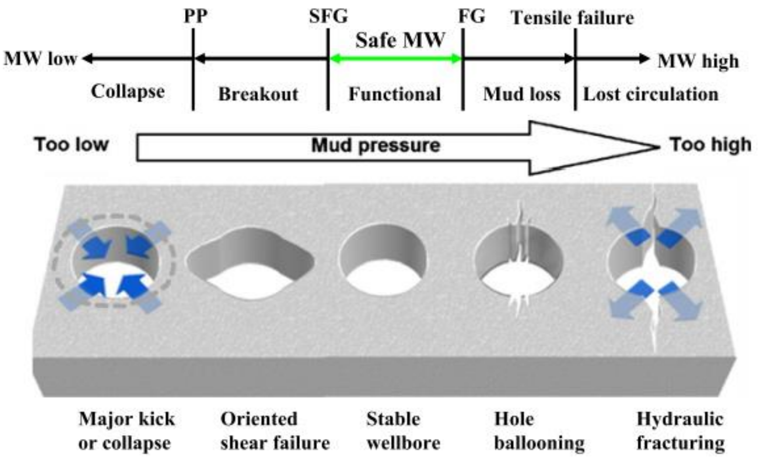
2.1 Abstract

Borehole instabilities pose significant challenges in drilling and completion operations, specifically in the areas where pre-existing fractures are intersected by the borehole. In-situ stresses play a vital role in failure mechanism around an excavation. In addition, discontinuities increase the probability of instability. Therefore, analyses of effect of in-situ stress in discontinuous media have significant importance in identifying efficient drilling methodologies. Numerical investigation on the behaviour of an unsupported vertical cylindrical borehole in heavily fractured rock mass is presented in this study. Discrete Element Model (DEM) based code Universal Distinct Element Code (UDEC) is used as the simulation tool. With taking into account the in-situ stress conditions in Cooper basin, South Australia, an unsupported borehole of 0.15 m radius in the centre of the model was simulated comprising of two fracture sets. The vertical stress applied correlates with the 1.5 km depth of the Cooper basin. The effect of fracture orientation and in-situ horizontal stress ratio (σ_H /σ_h) on the stability of the rock mass around the borehole was investigated. It has been shown that the induced stresses due to excavation lead to the development of a yielded zone around the borehole. Borehole stability criteria relevant to the extent of yielded zone and maximum displacement around the borehole were introduced into stability analysis. Results show that when the in-situ stress ratio increases, the rock blocks at borehole wall tend to move towards the centre of borehole, consequently yielded zone around the borehole increases. Similarly, the fracture orientation changes the angle of intersection between the borehole and fracture. This phenomenon, aids in increase of displacement as well as the location of block detachment. Furthermore, the change in fracture orientation highly influences the formation of yielded zone.

2.2 Introduction

Borehole stability is considered to be one of the most important problems in the drilling process. The deformations, breakouts and drilling induced failure can have significant consequences and may lead to well collapse. A lack of accurate wellbore stability analysis can bring up problems like washouts, breakout, borehole collapse, stuck pipe and mud loss (Peng and Zhang, 2007). Instability problems also add up to 10% of total drill time (Li et al., 2012) and may lead to abandoning the well. Extensive studies have been carried out for borehole instability, including analytical, experimental and few numerical studies. Fig. 2.1 demonstrates that when the mud pressure is higher than the formation pressure or pore pressure, the wellbore may experience ballooning and washout. Similarly, it can be observed in Fig. 2.1 that when the mud pressure is less than the shear failure gradient, the borehole experiences shear failure (Bell and Gough, 1979; Zoback et al., 1985; Tingay et al., 2005; Zoback, 2007). According to Fig. 2.1, one of the most important mechanical borehole stability problems is shear failure due to underbalanced drilling conditions.

Rock failure can occur as a result of rock strength anisotropy caused by weak bedding planes and natural fractures. In these cases, increased mud weight can further deteriorate the situation by mud loss (Santarelli et al., 1992). Modelling of such a geologic environment presents many challenges and requires coupling the in-situ stress, pore pressure, mud weight and fracture properties.



Where,

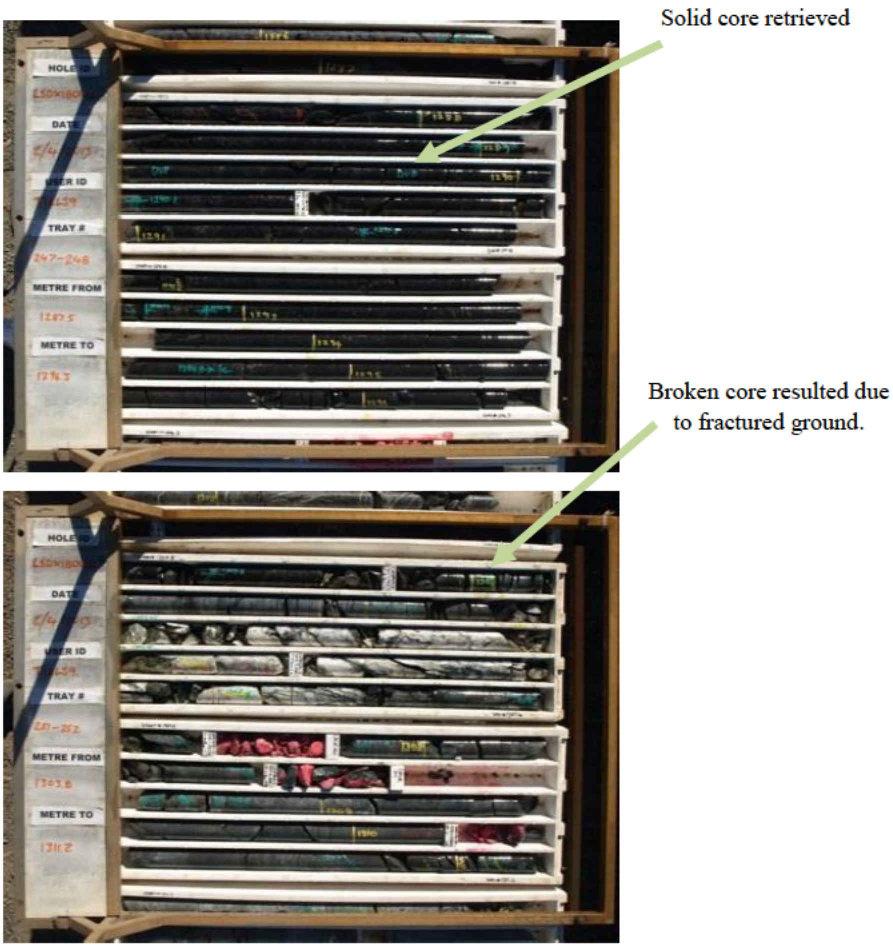
MW is Mud weight

SFG is Shear Failure Gradient

FG is Fracture gradient

Figure 2.1. Schematic relationship of wellbore failure (Zhang, 2013)

Whereas borehole stability in continuous media has been extensively studied, little attention has been paid to what happens in the case of fractured and interbedded formations. Recent field observations have shown that despite their relatively small diameters, boreholes can severely be affected by layering and the presence of natural fractures in the rock mass. Structurally controlled failures are the most common wellbore instability problems. For example, BHP Billiton drilled holes ranging from 800 to 2200 m depths in Mount Keith mine which is an open pit nickel mine in Western Australia. In this project it was experienced that, the general nature of the discontinuous ground condition makes the drilling process challenging. Similarly, Fig. 2.2 shows the pictures of core retrieved from a borehole at a mining exploration site in Western Australia at depth of 1287–1311 m operated by BHP Billiton. The core attained is from hard felsic and sheared puggy ultra-mafic zones. It can be observed in the Fig. 2.2 that as soon as the fractured ground is encountered core recovery is compromised.



Solid core retrieved

Broken core resulted due to fractured ground.

Figure 2.2 Core retrieved from the borehole from 1207 to 1311 meters at a mining exploration site in Western Australia

Various methods have been used to analyse the problem of borehole stability and to explain the mechanisms involved with borehole collapse (Adams, 1912; Plumb and Hickman, 1985; Aaden, 1988; McLean and Addis, 1990; Saltarelli et al., 1992; Ewy, 1998; Okland and Cook, 1998; Zhang et al., 1999; McLellan et al., 2000; Zhang and Roegiers, 2000; Haimson, 2001; Chen et al., 2002, 2003; Yamamoto et al., 2002; Moos et al., 2003; Haimson and Lee, 2004; Al-Ajmi, 2006; Fjaer et al., 2008; Kang et al., 2009; Ottesen, 2010; Salehi et al., 2010). However, the problem of borehole instability remains unsolved for the boreholes drilled in problematic situations such as unconsolidated formations, faulted and fractured rocks and salt domes. In a borehole intersecting fractured rock medium, borehole collapse has been explained by invasion of mud into the fractures. The invasion of mud increases the pore pressure therefore reducing the effective normal stress. A shear release then results in lateral displacement at the fracture plane. However, in underbalanced conditions where mud invasion is unlikely, predominant failure mechanisms are induced by stress concentration. Therefore, more sophisticated studies are required to devise a strategy to reach targeted depth safely.

Recently numerical methods have been utilized to understand the problem of borehole instability (Yamamoto et al., 2002; Zhang and Roegiers, 2002, 2005; Salehi et al., 2010; Hu et al., 2012). Continuum based, Finite Element Model (FEM) is commonly used by many researchers. However, FEM is unable to simulate the fracture nature of rock mass around borehole in heavily fractured condition (Jing, 2003). In order to model a medium with greater number of discontinuities DEM is assumed to be more appropriate to simulate rock behaviour (Jing, 2003).

One of the earliest works of borehole stability using numerical analysis in fractured rocks was carried out by Santarelli et al. (1992). These authors applied discrete element method (DEM) to the drilling data obtained from a problematic drilling site comprising of heavily fractured basalt and Tuff. They used conventional method of increasing mud weight to stabilize the well. Consequently, they concluded that high mud weights can increase the formation damage by penetrating into the fractures. Similarly, Yamamoto et al. (2002) presented a study of deviated borehole to understand the mode of failure on a weak plane. They concluded that penetration of fluid caused the fracture to slide and the severity increases with changing stress conditions. However, these numerical studies did not investigate the plastic deformation around the borehole induced by stress concentration.

This paper aims to investigate the effects of discontinuities orientation and in-situ horizontal stress ratio on borehole instability in heavily fractured condition taking into account in-situ stress conditions of Cooper basin in Australia. A series of numerical analysis on a borehole drilled in fractured rock mass are conducted using two-dimensional discrete element method (DEM) code UDEC (Universal Distinct Element Code).

2.3 In-situ stress state in Cooper basin

Cooper basin is Australia’s most prolific onshore basin where hydraulic fracturing treatments are reportedly being problematic. More than 3000 exploration and production boreholes have been drilled in the Cooper basin. One of the problems to achieve the targeted drilling depth is the orientation and magnitude of maximum horizontal stress

(σ_H) in the Cooper basin. Details on tectonic evolution of the Cooper basin are discussed by Apak et al., (1997). The reader is directed to this study for in depth details of geological and tectonic evolution of the basin. The interaction of in-situ stresses with the pre-existing fractures and faults have been investigated by Reynolds et al., (2005) and Nelson et al. (2007) to understand the fracture propagation and permeability. Boreholes drilled intersected various natural fractures which were observed on the image logs (Nelson et al., 2007). Additionally, few studies have investigated the distribution and density of fractures within the area of Cooper basin (Backé et al., 2011; Abul Khair et al., 2012). However, borehole stability has not been deeply investigated in this area. In particular the effect of different in-situ stress ratios and their interaction with fracture orientation has not been studied so far.

Reynolds et al. (2006) constrained the magnitude of principal stresses in wells Bulyeroo-1 and Dullingari North-8 that illustrate a predominant strike slip-stress regime ($\sigma_H > \sigma_v > \sigma_h$) at depths ranging from 1 to 3 km. At greater depths strike slip stress regime change into reverse fault stress regime ($\sigma_H > \sigma_h > \sigma_v$) with minimum horizontal stress magnitude reaching equal to the magnitude of vertical stress magnitude. The in-situ stress magnitudes are extracted from Reynolds et al. (2006) for this study and are tabulated in Table 2.1.

Table 2.1. In-situ stresses extracted from Reynolds et al (2006) at the depth of 1.5 km

In-situ stress	
Maximum Horizontal Stress σ_H (MPa)	45
Minimum Horizontal Stress σ_h(MPa)	30
Vertical Stress σ_v(MPa)	30

2.4 Modelling method

DEM was initially presented by Cundall (1971) as assemblage of blocks (Jing, 2003). In the DEM, a rock mass is represented as assemblage of discrete blocks. Interface between the blocks is characterized as boundary condition (discontinuity). The contact forces and displacements at the interface are calculated by a series of equations. The calculations performed in the DEM alternate between application of force-displacement law and newtons law. Newton's law determines the motion of blocks as a result of forces acting on them and force-displacement law update the forces at the contacts. New velocities for each block are updated at every time step until equilibrium is attained (Itasca, 2004). The velocity for each time step can be expressed as follows:

$$\mu_i^{(t+\frac{\Delta t}{2})} = \mu_i^{(t-\frac{\Delta t}{2})} + \left(\frac{\sum F_i^{(t)}}{m} + g_i\right) + \Delta t \qquad (2.1)$$

$$\theta^{(t+\frac{\Delta t}{2})} = \theta^{(t-\Delta t/2)} + \left(\frac{\sum M^t}{I}\right) \Delta t \qquad (2.2)$$

Where, θ is angular velocity of block around centroid, *i* is moment of inertia $\sum M$ is total moment, μ_i is velocity components of block centroid and g_i is gravitational components of block centroid.

The overall governing equation, which is used for 2D assemblages of blocks, can be written as:

$$m\mu^t + \alpha m\mu^t = \Delta F \qquad (2.3)$$

Where, *m* is the mass of the block at centroid μ is the incremental displacement, α is the mass damping coefficient, *t* is time and ΔF is the incremental force.

2.4.1 Block discretization

In this study blocks are represented as polygons with a finite number of straight edges. Furthermore, the deformable blocks are further divided into a finite number of constant strain triangles which form the mesh of tetrahedral zones. These zones deform when the stress conditions change (Fig. 2.3).

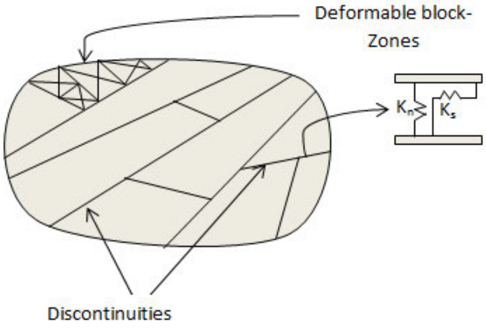


Figure 2.3. Schematic representation of fractured rock mass in DEM

2.4.2 Rock joint representation

DEM represents rock joint as a contact surface formed between two block edges. The contact defining algorithm determines the type of contact and the maximum gap. As shown in Fig. 2.3, the interaction between two connecting blocks is mechanically characterized by a finite stiffness (spring) in the normal direction and a finite stiffness and friction angle in the tangential direction (Nicolson and Hunt 2004; Camac and Hunt 2009). The deformation of the springs determines the amount of forces developing at the contacts which can be resolved into normal (ΔF_n) and shear components (ΔF_s).

$$\Delta F_n = K_n \, \Delta \mu_n \tag{2.4}$$

$$\Delta F_s = K_s \Delta \mu_s \tag{2.5}$$

Where K_n and K_s are normal and shear stiffness of the contact, and $\Delta\mu_n$ and $\Delta\mu_s$ are normal and shear displacement increments.

Finally, the stresses calculated at grid points located along contacts are incorporated in the failure criteria. Shear behaviour of the fracture is modelled as an elasto-perfectly plastic model where shear stress ($\mathcal{T}_s$) is limited by combination of Cohesion (c) and friction angle (ϕ) following the Coulomb failure criteria expressed as below.

$$|\tau_s| \leq C + \sigma_n \, tan\phi \tag{2.6}$$

2.4.3 Block deformation

This study incorporates discretised blocks. The blocks that are discretised are able to deform as a result of applied load (Fig. 2.3). The complexity of deformation is dependent on number of elements. The density of Zones is kept constant throughout the model for this study. The deformation for every time step is estimated at the vertices of the triangular elements (Itasca 2004). Equation of motion for each grid point can be written as:

$$\ddot{u}_i = \frac{\int s \, \sigma_{ij} n_j ds + F_i}{m} + g_i \tag{2.7}$$

Where,

s is the surface enclosing the mass m at the grid point, n_j is the unit normal to s, F_i is the total external forces applied on the grid point and g_i is the gravitational acceleration.

2.4.4 Time step

As the simulation progresses position of the contacts update constantly until numerical equilibrium is attained. A limiting time step is required to satisfy Mohr-Coulomb stability criterion of rock deformation and block displacement. The time step is estimated as:

$$\Delta t_n = 2 \min \left({}^{m_i}/_{K_i} \right)^{1/2} \tag{2.8}$$

Where m_i is the mass associated with block node i and K_i is the measure of stiffness of the elements surrounding the node.

2.4.5 Boundary conditions

In DEM simulation choice of boundary condition plays a vital role and has a significant impact on the response of the model. Displacement boundary condition in continuum modelling is common to restrict or define the boundary displacement and traction boundary conditions along which stresses are specified (Itasca, 2004). In deformable blocks, displacements are specified in terms of velocities at given grid points. At a stress boundary forces are derived as follows:

$$F_i = \sigma_{ij}^{b} \, n_j \, \Delta s \tag{2.9}$$

Where, n_j is the outward normal vector of the boundary segment and Δs is the length of the boundary segment over which the stresses $\sigma^{b}{}_{ij}$ acts,

The state of stress in Cooper basin is laterally variable. The boundary stress conditions are adopted from Reynolds et al. (2006) which represents strike slip stress regime at the depth of 1500 meters (Table 2.1). This data is then manipulated to perform parametric study to investigate the effect of in-situ stress ratio.

2.5 Material and methodology

2.5.1 Modelling conditions

In this study, a 2-D plane strain numerical model has been generated using UDEC (version 4.0). The model dimensions are considered to be 3 x 3m. A vertical borehole of 0.15m radius is present at the centre of the model. Material properties of the synthetic shale have been selected from Chen et al. (2003). Model parameters are listed in the Table 2.2

Table 2.2 Modelling properties extracted from (adopted from Chen et al., 2003)

Intact rock properties	
Density (kg/m3)	2278
Bulk modulus (GPa)	18.87
Shear modulus(GPa)	7.72
Friction angle (degree)	36.2
Cohesion (MPa)	6.3
Dilation angle (degree)	0
Tensile strength (MPa)	2.07

Fracture properties	
Normal stiffness (GPa)	9
Shear stiffness (GPa)	6
Cohesion (MPa)	0
Friction angle (degree)	32
Residual aperture (m)	$1.25e^{-4}$
Zero normal stress aperture (m)	$2.5e^{-4}$

The extent of model boundary is considered so that the effect of deformation around the wellbore in the centre of the model is not affected by the model boundary. Furthermore, stress boundary conditions are applied to make sure the model is representative of far field stress conditions. As the primary aim of this study is to investigate the stability of borehole in relation to fracture orientation and in-situ stress, two fracture sets perpendicular to each other are considered to be running across the model at an angle α_1 and α_2. A schematic representation of model geometry is presented in Fig.2 4.

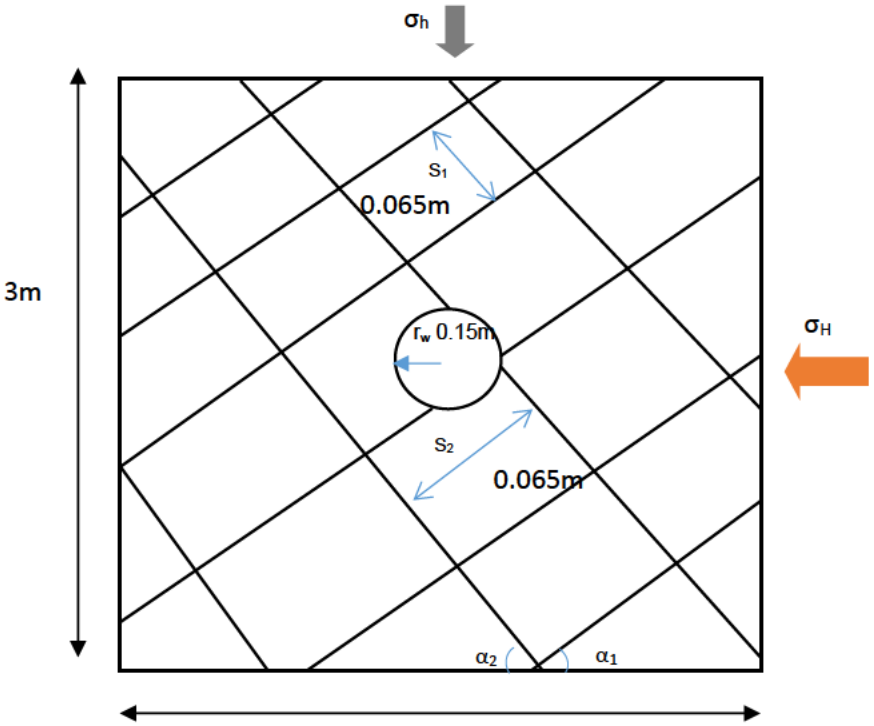


Figure 2.4. Model geometry

Once the material and fracture properties are added, a stress boundary is selected. Before a simulation can be processed initial state of equilibrium is achieved under in-situ stresses and zero pore pressure. The model is now simulated to attain equilibrium until stress boundary conditions are satisfied.

To simulate the borehole response; the borehole is first excavated by removing blocks. The code written for the model applies force and is designed to generate a stress boundary on the walls surrounding the model. This results in changing displacements of the blocks where the effective stress increases the threshold. Iterations continue until equilibrium is attained. The flow chart for the numerical model is presented in Fig. 2.5.

2.5.2 Constitutive relation

A constitutive model is applied to the deformable blocks which were discretised earlier. In this study, the blocks of intact rocks are assumed to undergo linear elastic-plastic deformation with Mohr-Coulomb failure criterion (Equation 7) while the displacement at discontinuities is determined by Coulomb slip model (Equation 6).

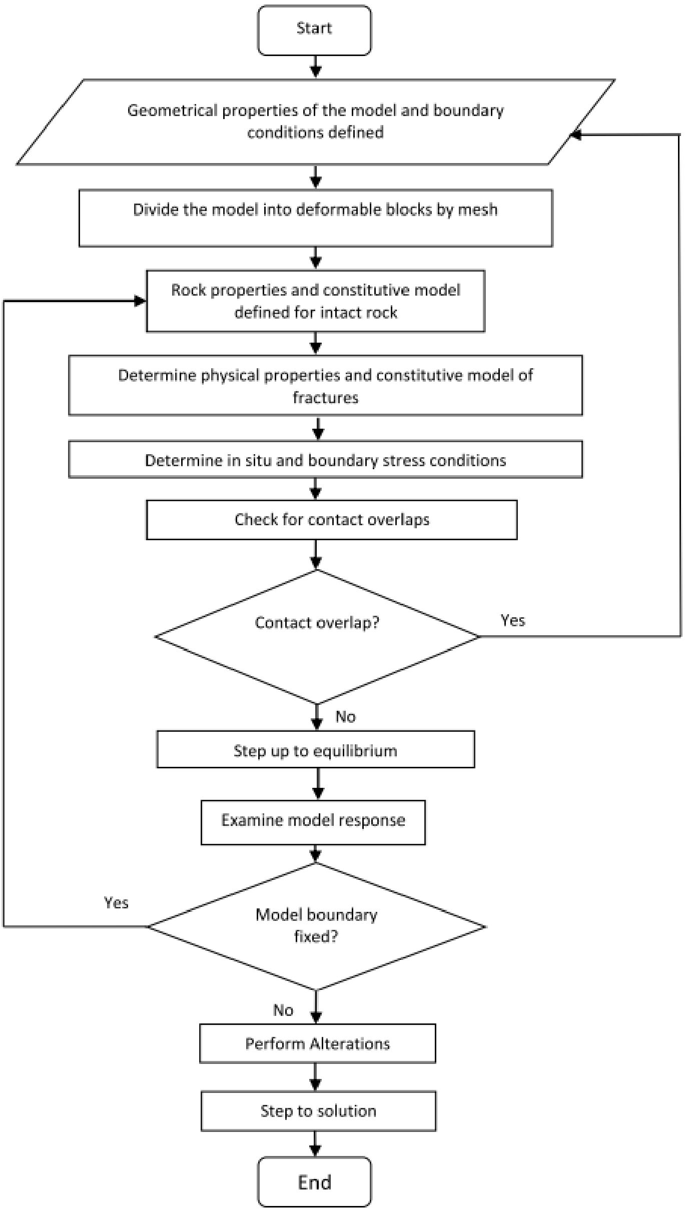


Figure 2.5. Flow chart of numerical modelling

2.6 Borehole stability criteria

In this study 30 observation points were marked around the borehole profile to measure the displacement of blocks during simulation. The model is considered in a planar orientation with north representing towards the top. At the end of model run each observation point is used to plot the displacements along the borehole profile. Two criteria were used to investigate the stability of a vertical borehole.

2.6.1 Maximum displacement

Borehole's wall may fail when the induced stress due to excavation exceeds the tensile or the shear strength of jointed rock mass. The far field stress and the specific borehole orientation (In this study vertical) need to be determined before the analysis. Displacements around the borehole profile were achieved using the observation points marked in the modelling setup. Fig. 2.6 shows block movement towards the borehole for case 1c (α_1=15°). The maximum displacement measured in this case is 0.018 m.

The way in which a borehole responds to the drilling operation is dependent on the complex geological structures, far field and local stresses and operational parameters. Therefore, it is not possible to determine a definite threshold of displacement of rock blocks for a particular condition. It is assumed that some degree of disturbance will be a common practice in the wells with fractured rock medium. Therefore, an overall change in borehole size with a threshold of 10% is assumed to be stable. Maximum displacement values attained from observation points are used to estimate the change in borehole size according to the simple relation presented below.

$$Relative\ displacement\ (\%) = \frac{Maximum\ displacement}{Borehole\ diameter} * 100 \qquad (2.10)$$

The value of 0.032 m corresponds to the 10% displacement around the borehole. Which is considered to this study an optimal maximum displacement of 0.0319m is considered to be the threshold of borehole stability.

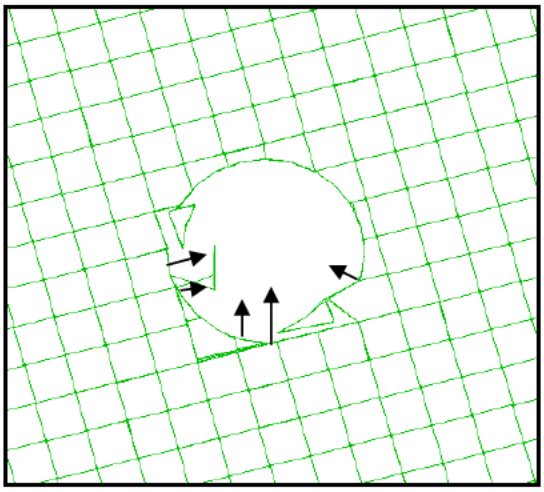
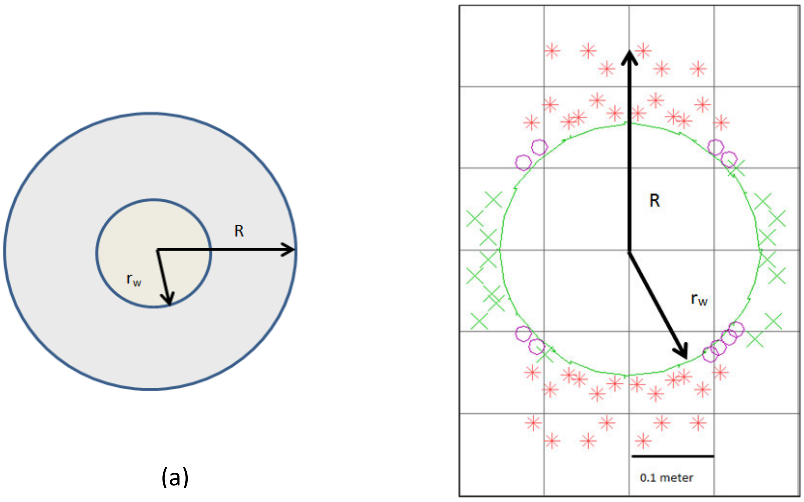


Figure 2.6. Displacement vectors, showing magnitude of displacement

2.6.2 Normalized yielded zone radius

As shown in Fig. 2.6, the extent of yielded zone around a borehole as a result of induced stresses is measured using average normalized yielded zone radius (Fig. 2.7a) similar to McLellan et al. (2000), Hawkes (2007) and Salehi et al. (2010). Figure 2.7b illustrates a magnified UDEC model showing the extent of deformation around borehole. The normalized average plastic zone radius is the ratio of average of radius yielded zone (R) to the radius of the borehole (r_w). Hawkes (2007) articulates that the Normalized yielded zone radius 1.4 to 1.5 corresponds to the problem free drilling environment. However, this threshold can be sensitive to various factors and care should be taken using these values (Hawkes, 2007). In this study 1.3 is considered to be a threshold for the stability of a borehole (McLellan et al., 2000, Hawkes, 2007, Salehi et al., 2010).

The aim of this study is to investigate stability of a borehole in heavily fractured rock and failure mechanisms that are solely induced by different fracture orientations and in-situ stress conditions. Simulation of overbalanced condition with considering fluid penetration into the rock mass is beyond the scope of this paper. The authors are currently working with a three-dimensional discrete element code 3DEC to generate a model with overbalanced drilling conditions to investigate the failure mechanisms and effect of fluid influx on the overall stability of a borehole. The results will be published in near future.



(a)

(b)

Figure 2.7. (a) Average yielded zone radius schematic representation. (b) UDEC representation of yielded zone radius for case 6c

2.7 Parametric study

The results obtained in this study are discussed below as quantitative evaluation of yielded zone and the maximum displacement around the borehole. For each case of fracture orientation and in-situ stress ratio, the numerical model was run under the same assumptions on the intact rock behaviour and fracture properties. Each model was run until the equilibrium criterion was satisfied. The corresponding properties for discrete element model are enlisted in Table 2.2. This study primarily aims to investigate the influence of fractures that intersect the borehole and the extent of influence due to change in far field stress conditions on the stability of a borehole. Impact of mud which can have negative impact on the stability of fractured rocks (Santarelli et al., 1992) is not incorporated within the model. Therefore, deformations are related to underbalanced drilling conditions of rock mass are investigated in this study. Simulated cases are tabulated in table 2.3.

Table 2.3. Modelling cases used in this study

Case	α_1 orientation	α_2 orientation	σ_H/σ_h
1a	15°	285°	1
1b	15°	285°	1.5
1c	15°	285°	2
2a	30°	300°	1
2b	30°	300°	1.5
2c	30°	300°	2
3a	45°	315°	1
3b	45°	315°	1.5
3c	45°	315°	2
4a	60°	330°	1
4b	60°	330°	1.5
4c	60°	330°	2
5a	75°	345°	1
5b	75°	345°	1.5
5c	75°	345°	2
6a	90°	360°	1
6b	90°	360°	1.5
6c	90°	360°	2

2.7.1 Effect of in-situ stress ratio

In-situ stress ratio is an integral part of borehole instability modelling (Zoback, 2007). The stress regime and in-situ stress ratio have significant impact on the mode by which failure occurs at the borehole wall (Zhou et al., 1994). A numerical analysis is carried out in this study to investigate the influence of ratio of horizontal stresses on the instability of a borehole at a depth of 1500m. Magnitude and location of displacement and the depth of yielded zone are used as stability criteria.

For an intact borehole, it is well established that with increase in horizontal in-situ stress ratio, borehole becomes less stable. Additionally, the borehole breakouts are formed in the direction of maximum horizontal stress (σ_H). However, in a borehole which intersects pre-existing planes of weakness or discontinuities, failure can also occur in other directions in addition to σ_H orientation. The failure mechanisms at such borehole is complex and not fully understood (Zhang, 2013).

Three different cases of stress ratio (Case a, b and c) are analysed in this study. Each case is investigated for different fracture orientations (Case 1-6). Fig. 2.8 shows the maximum displacements at the borehole wall as a function of fracture orientation for three horizontal stress ratios modelled. It should be noted that the values on x-axis represents α_1 values. Dotted line in Figs. 2.8 and 2.9 represents a threshold of stability used in this study which indicates normalized yielded zone radius of 1.3 and maximum displacement of 0.0319m. Therefore, the cases above this line are considered unstable.

From Fig. 2.8 it is apparent that the magnitude of displacement increases with the increase in in-situ stress ratio, generally. Maximum displacement 0.058m is observed for Case 4c (α_1=60°) making it the highest unstable case. However, for case 2 (α_1=30°), the displacement tends to decrease consequently as a result of increase in stress ratio.

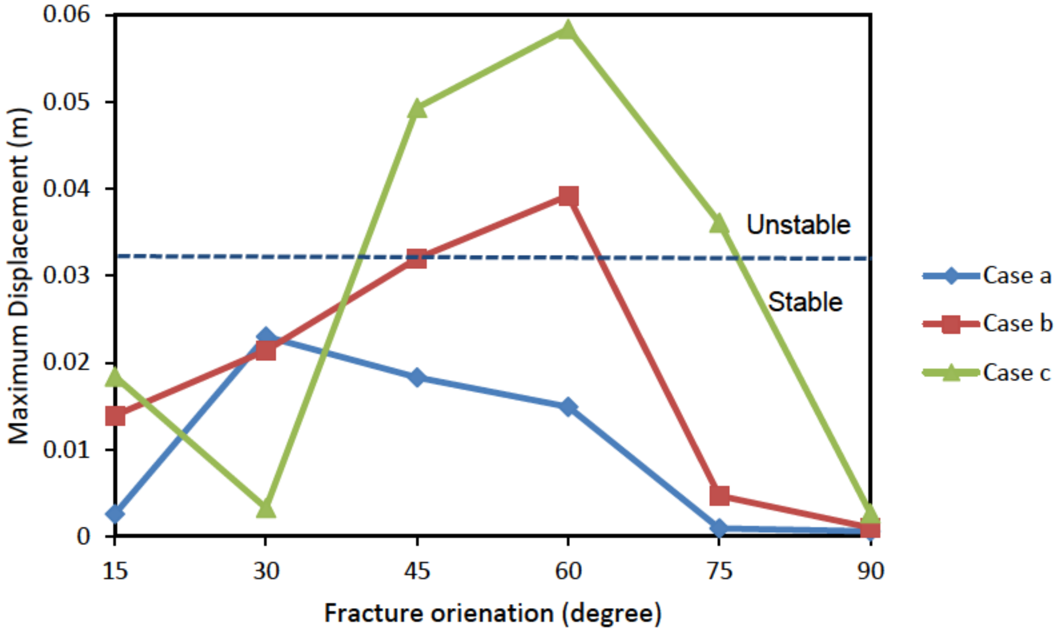


Figure 2.8. Maximum displacements as a function of fracture angles

The reason behind this phenomenon can be explained by the locked in stresses. Homberg, et al. (1997) in addition to other researchers observed that the discontinuities tend to perturb the local stress field and stress concentrates on the fault tips known as locked in stresses. These perturbations then affect the permeability and orientation of fracture by changing the aperture sizes. Similarly, in addition to physical boundaries these stress boundaries can affect the behaviour of rock response to the applied load (McKinnon, 2001). In addition, it can be seen that the amounts of displacements when two joint sets are perpendicular and parallel to σ_H are the lowest magnitude (α_1=90°). This is the most stable condition, where joints have little chance to slip on each other and the possibility of block movement is restricted. Fig. 2.9, confirms this finding.

Figure 9, graphically represents the extent of normalized yielded zone radius around the borehole as a function of fracture orientation for the three in-situ stress ratios investigated as part of this study. The increase in yielded zone radius with increase in horizontal stress ratio clearly correlates with the increase in displacement (Fig. 2.9). If we compare Figs. 2.9 and 2.10 it can be observed that the displacement for case 6c (α_1=90°) is merely a fraction in Fig. 2.9. However, the yielded zone radius for the same case shown in figures 2.9 and 2.11 clearly depicts that the rock mass around is in the plastic zone and is highly unstable. Laboratory experiments have demonstrated that rock strength decreases with increase in time. Therefore, the rock blocks will start to detach from the borehole wall with time, until it is cased within the timeframe. An increasing trend in the extent yielded zone around borehole as a function of in-situ stress ratio can be clearly observed in Fig. 2.11 and can be compared to the graphical representation of yielded zone in Fig. 2.9.

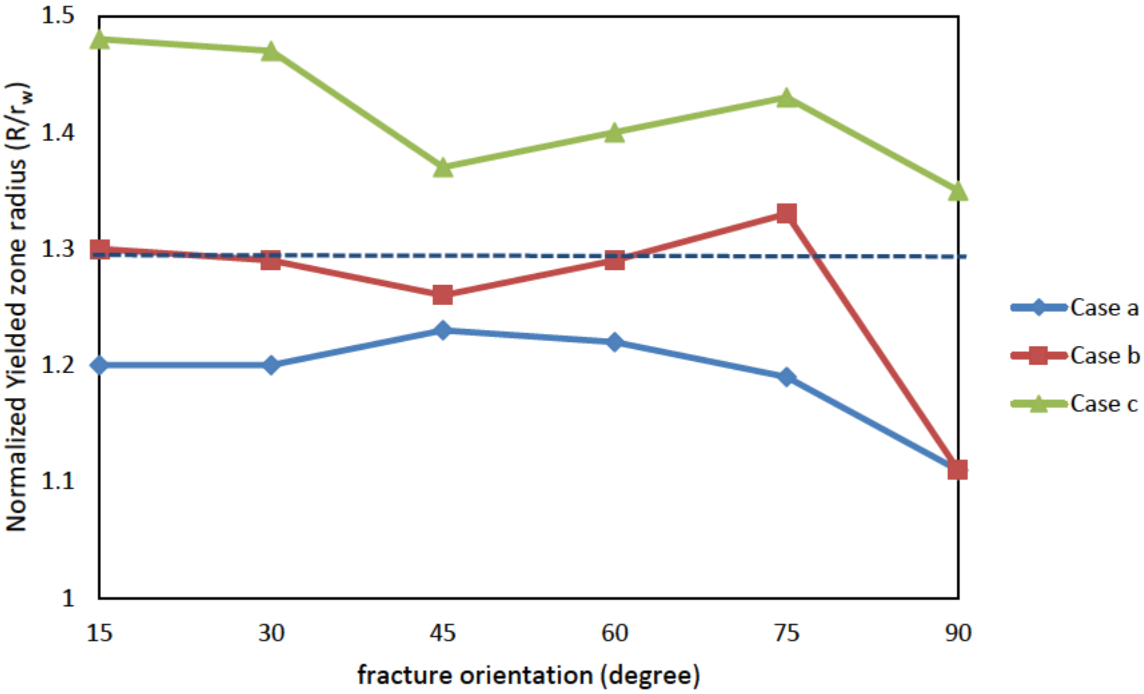
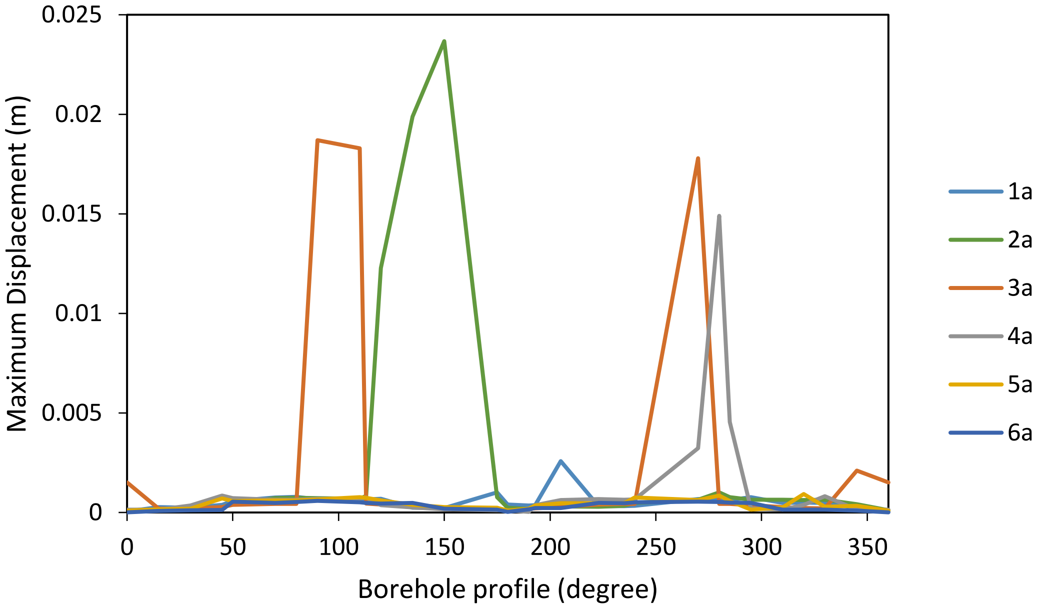
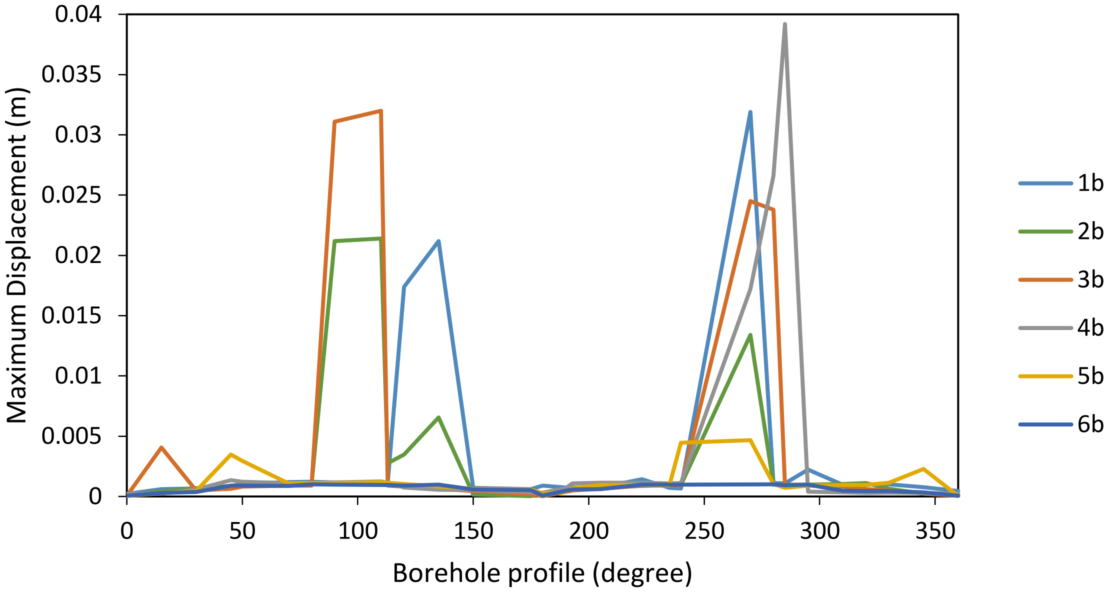


Figure 2.9. Normalized yielded zone radius as a function of fracture orientation

Figure 2.10 represents the displacement for each observation point around the borehole profile for the 18 cases modelled (Table 2.3). It is observed in Fig. 2.10a which represents effect of fracture orientation in isotropic stress condition that the displacement magnitude fall below the threshold of stability. The maximum displacement observed in this case is 0.023m. Consequently, in Figs. 2.10b and 2.10c displacement magnitude increases which is primarily driven by increase in in-situ stress ratios. However, if we compare Figs. 2.10 a, b and c; we can observe a general trend in the profile for each case, the reason being the angle at which fracture intersects the borehole.



(a)



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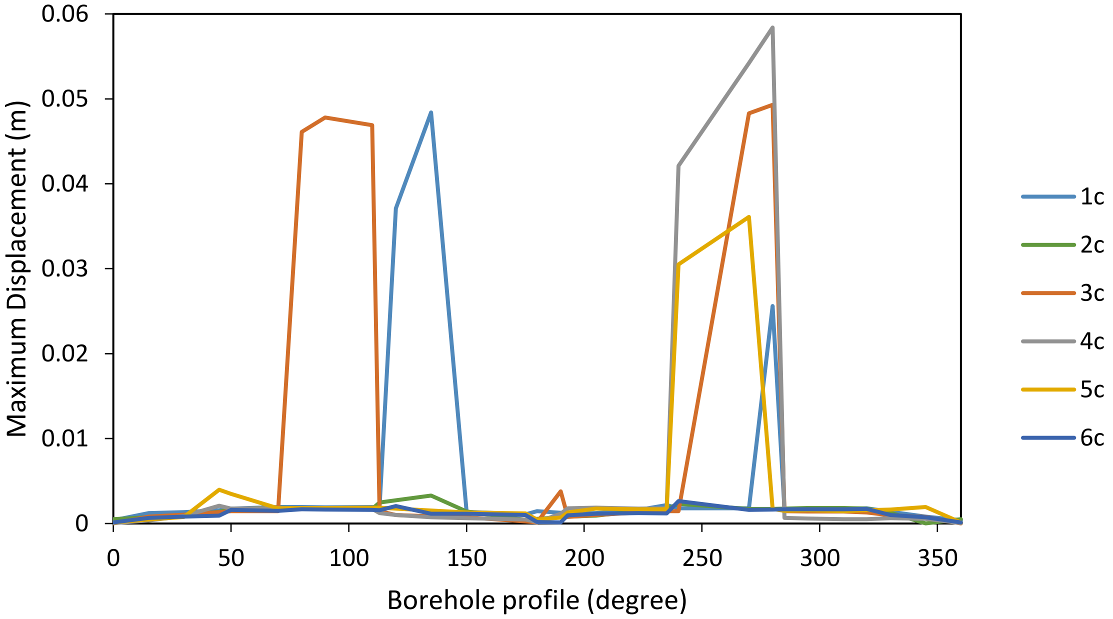

(c)

Figure 2.10. Displacement at borehole wall for a) $\sigma_H/\sigma_h=1$, b) $\sigma_H/\sigma_h=1.5$, c) $\sigma_H/\sigma_h=2$

2.7.2 Effect of fracture orientation

Simulations were conducted by varying fracture orientation while keeping all other factors constant. It was observed that the change in fracture orientation had significant influence on the maximum displacement and location of slipping blocks. In Fig. 2.8, displacement is observed to be minimum for the extreme end cases (α_1=15° and α_1=90°) while middle cases (α_1=30°, α_1=45°, α_1=60° and α_1=75°) attain increasing displacements. We suggest that it is because of the intersection of the discontinuity with the borehole and orientation of σ_H which limit block movement. For isotropic stress conditions in case a, α_1=30° is seen to have highest displacement magnitude. However, for anisotropic stress states (Case b and c), α_1=60° is observed to have highest values of displacement. This is mainly because when α_1 is equal to 30 and 60, discontinuities under induced stress conditions have more tendencies to slip at the borehole wall.

Normalized yielded zone radius is represented in Fig. 2.9 show little variation in the profile. This help us to understand that change in fracture orientation may does not have a significant effect on the yielded zone around the borehole. However, presences of discontinuities promote block displacement to a significant degree (Fig. 2.9). It can be observed in Fig. 2.9 that case 6 (α_1=90°) is relatively stable then other cases. The normalized yielded zone radius for case 4c (α_1=60°) is 1.4 (Figs. 2.9 and 2.11) while the displacement tends to be 0.058m. All the cases exceeding the threshold of 0.0319m displacement or 1.3 normalized yielded zone radius, is considered unstable in this investigation.

As from the literature review we know that the borehole breakout should be formed in the direction minimum horizontal stress (σ_h) in continuum rocks which in this study aligns with the y-axis of the model. However, displacement of the blocks can be significantly affected by the presence of discontinuities (Zhang, 2013). The key point observed in this analysis is the location of block displacement changes significantly with the fracture orientation (Fig. 2.10), this phenomenon is evident of the fact that discontinuities have a significant effect on the mechanism of failure at the borehole wall. Additionally, the magnitude of displacement also varies with fracture orientation.

Fig. 2.11 represents development of a yield zone around borehole for each case tabulated in Table 2.3. The extent of yielded zone around the borehole in Fig. 2.11 is well correlated with Fig. 2.9. This representation clearly depicts the key points mentioned earlier in the discussion and correlates with the basic idea of increase in instability with increase in in-situ stress and fracture orientation.

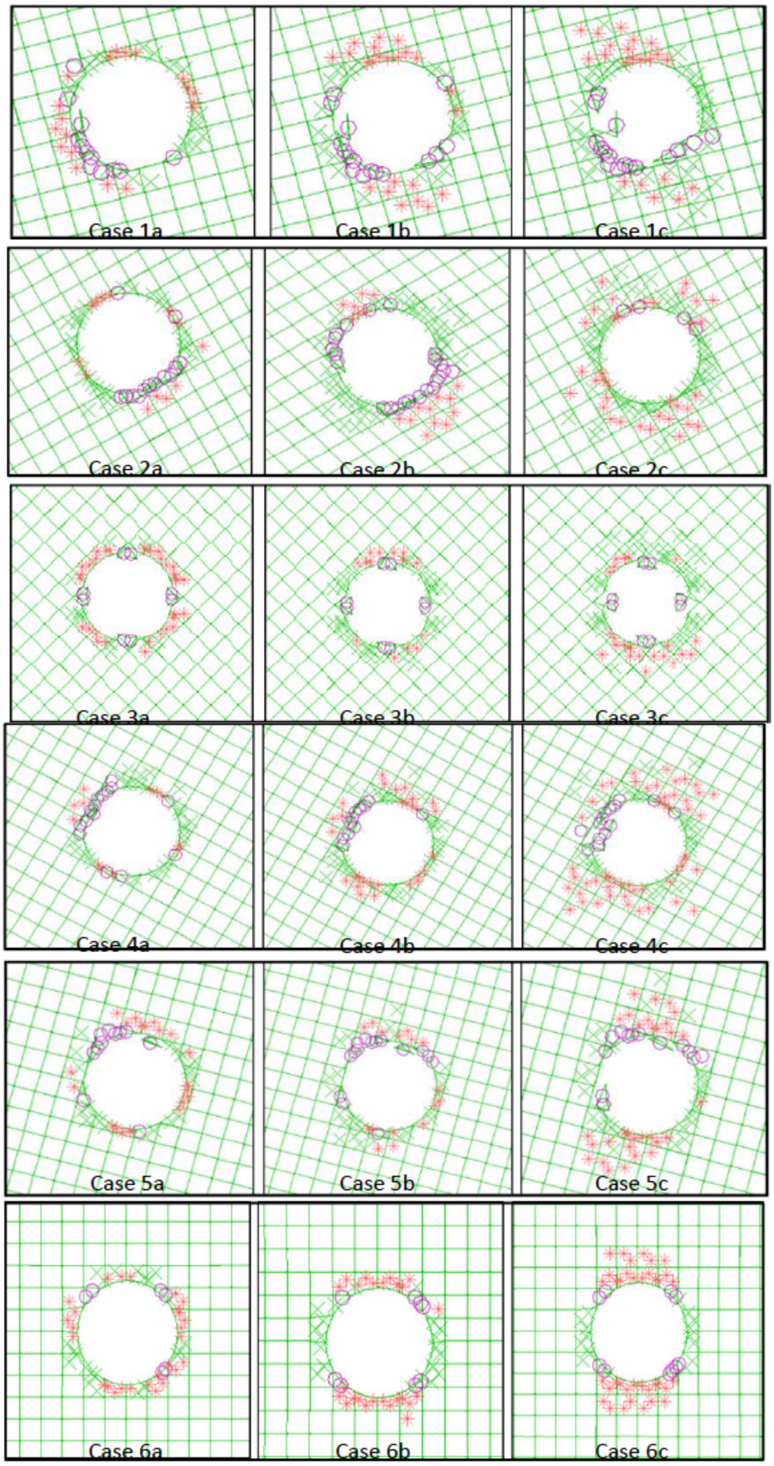

Figure 2.11. Yield zone around the borehole for 18 cases.

2.8 Discussion

When borehole is drilled stresses redistribute themselves and concentrate around the borehole. Since, the model is simulated with underbalanced drilling conditions; the failure mechanism anticipated here is deformation and movement of rock blocks, triggered by pre-existing plane of weakness, toward borehole due to stress concentration. This generates a disturbed plastic zone around the borehole. The extent of plastic zone has been considered as stability criterion in this study.

Rock blocks at the borehole wall which are intersected by fracture result in detachment at the fracture plane resulting in “spalling off” from the borehole wall because of closely spaced discontinuities and shear stress build up in borehole walls which exceeds the shear strength of discontinuities. It is apparent in Fig. 2.11 that the orientation of fracture and in-situ stress anisotropy controls the spalling mechanism around the borehole. On the other hand, localized concentration of stresses also results in slip along fractures which aids in deformation around the borehole increasing the extent of plastic zone.

2.9 Conclusion

Borehole stability is critically important for drilling, particularly in deep seated fractured formations. In this study, the influence of effective stress ratio and fracture orientation is investigated using discrete element method. Two borehole stability criteria on the basis of maximum displacement and normalized yielded zone were used in this study to evaluate borehole failure mechanism in different modelling conditions.

The following conclusions are drawn from this study.

1- After drilling the borehole, the in-situ stresses which were formerly under equilibrium, altered and an induced stress concentration is experienced around the borehole. Studies have shown that because of the presence of discontinuities, the induced tangential stress exceeds the strength of fractured formation which leads to the collapse of borehole wall.

2- Comparison of response of a borehole in fractured media and different in-situ stress ratios has shown that after the model achieves equilibrium, the displacement of rock blocks increased consequently for each case as a result of increase in in-situ stress ratio. Similarly, the yielded zone increased subsequently with the increase in in-situ stress ratio. The difference in displacement and yielded zone is justified since the compressive stresses applied on the model are different. Isotropic stress condition ($\sigma_H/\sigma_h=1$) is observed to be the most stable scenario. However, it should be noted that in deep ground in-situ stress conditions are usually anisotropic.

3- In this study, anisotropic stress ratio ($\sigma_H/\sigma_h=2$) is observed to be highly unstable. However, such a condition is not very common in the subsurface. On the other hand, anisotropic stress ratio ($\sigma_H/\sigma_h=1.5$) is found to be critical for borehole stability analysis. Rotation of fractures during fracturing treatments, production issues and borehole stability problems have been reported from Cooper basin under similar stress conditions.

4- Sensitivity analysis conducted to study the influence of the fracture orientation showed that with the increase in the angle of discontinuities from 15° to 60°, the displacement of rock blocks increased leading to deteriorating condition of the borehole However, when the fracture angle was further increased from 60° to 90°, the block displacement decreased to significant degree. On the other hand, there is no significant change in the profile of yielded zone with changing fracture angles. Although for three modelled stress ratios for $\alpha_1=90°$, yielded zone shows minimum values.

5- Another important phenomenon observed that with the change in fracture orientation, the location of blocks which displaced changed accordingly. The study of the influence of fracture angle confirms that the orientation of discontinuity plays a vital role in the stability of borehole in fractured rock mass and the failure is not always in the direction of σ_H.

6- Shear failure along the weak planes is found to be the predominant mode of failure at the borehole wall. Additionally, the severity of failure is observed to be increasing with increasing stress ratio.

2.10 Acknowledgements

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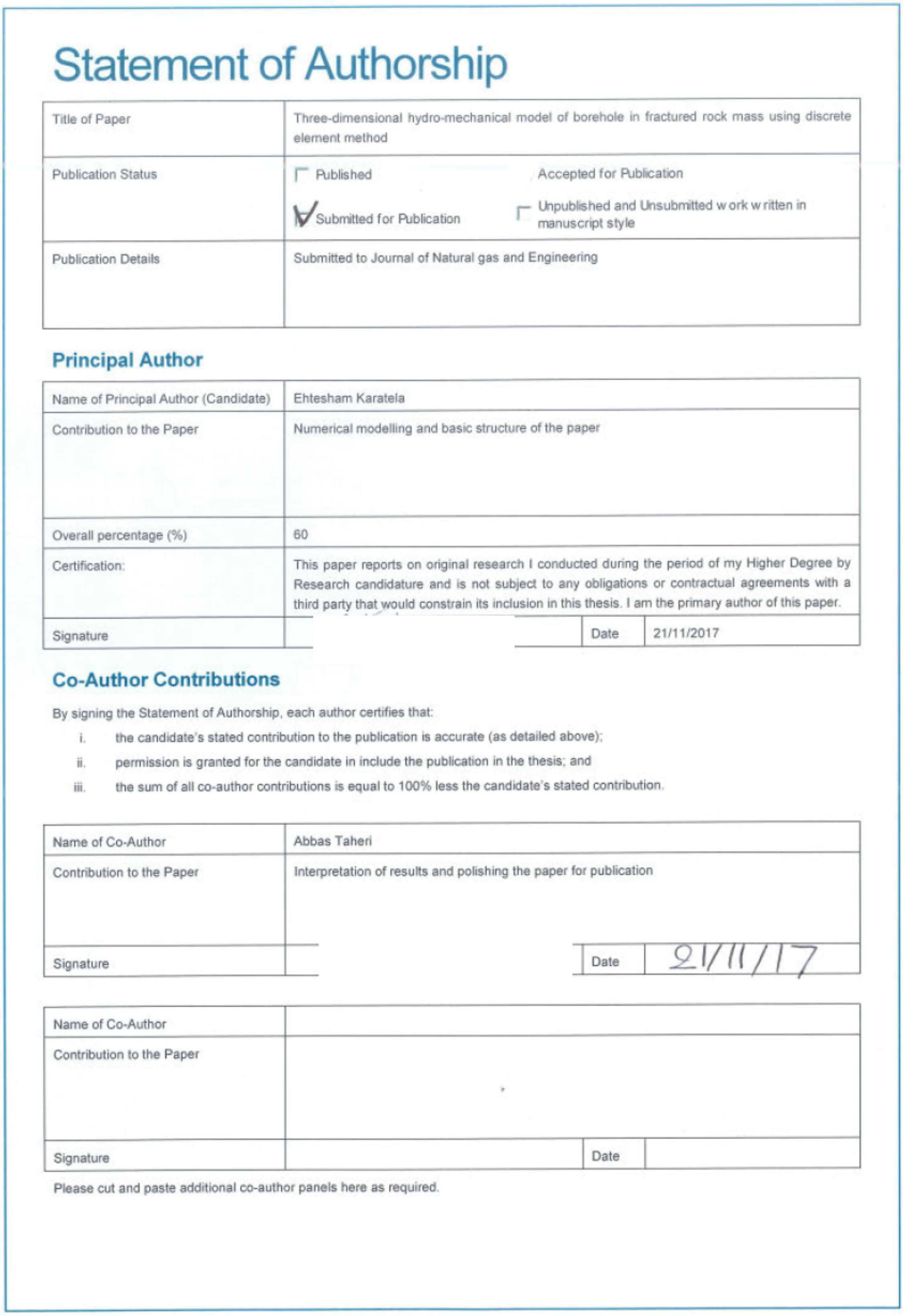
Statement of Authorship



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Contribution to the Paper	Numerical modelling and basic structure of the paper		
Overall percentage (%)	60		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
Signature		Date	21/11/2017

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);

ii. permission is granted for the candidate in include the publication in the thesis; and

iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

Name of Co-Author	Abbas Taheri		
Contribution to the Paper	Interpretation of results and polishing the paper for publication		
Signature		Date	21/11/17

Name of Co-Author			
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Chapter 3

Paper 2: Three-dimensional hydro-mechanical model of borehole in fractured rock mass using discrete element method

3.1 Abstract

Borehole stability, in heavily fractured rock mass has been a significant issue in deep earth resources exploration and extraction. In this study, a three-dimensional model using 3DEC is developed to simulate a borehole drilled in fractured rock mass. A model with overbalanced drilling conditions is simulated in this study. In doing so, different depths of a borehole, MB-1 borehole, in Northern Perth basin was simulated. The developed model was validated against log measurements of Caliper log and strength of rock is found as a governing factor in controlling the stability. Then, hydro mechanical modelling was carried out and it was observed that high mud flow rates and high pore pressure increased the instability around borehole. Furthermore, a parametric study was performed to investigate the influence of viscosity and fluid flow on the stability. Shear displacement linearly increase with an increase in flow rate while fluid pressure decreases due to increase in fractures aperture with an increase in flow rate. Similarly, increase in viscosity caused increase in fracture shearing and therefore instability around borehole.

3.2 Introduction

Borehole stability is a major issue faced in petroleum and mining industry as it can result in significant expenditures. Thus, having a substantial impact on reservoir production, operation and exploration. Stability of circular boreholes have been considered and studied in multiple disciplines. New challenges have emerged and it has become important to study borehole stability in unconsolidated formations (Hashemi et al., 2014, 2015), heavily naturally fractured rock mass (Karatela et al., 2016) and deep-seated formations (Camac and Hunt, 2004).

A number of experimental (Santarelli et al., 1992; Ohoka et al., 1997), analytical (Moos et al., 2003; Fjar et al., 2008; Zoback, 2007) and numerical methods (Zhang et al., 1999; Xu et al., 2004; Zhang and Roegiers, 2005; Karatela et al., 2016) have been used for borehole stability analyses. However, mechanism of borehole failure in fractured rock mass is very complex and has not been completely understood. With the advancement in numerical methods, we have the ability to simulate the rock mass to investigate failure mechanisms in rock mass. For instance, Zhang and Sanderson (2002) modelled a circular borehole in fractured rock mass. Their model showed that the borehole was highly susceptible to deformation and block displacement. Similarly, Barton et al. (2002) carried out a numerical study of a tunnel in fractured rock mass which investigates blocky movement of rock blocks from the tunnel wall under compression. Similarly, Hashemi et al. (2012) simulated as vertical borehole with PFC3D and explained the detachment of unconsolidated soil particles from the borehole wall. Hydro-mechanical processes are usually studied as part of stress dependant permeability (Min et al., 2004) or fluid injection and development of hydraulic fracture (Vishal et al., 2015, Lei et al., 2015). However, effect of groundwater pressure and drilling fluid on borehole stability have not been thoroughly Investigated.

To improve the understanding of the relationship between hydraulic and mechanical processes in fractured rock mass, several studies have used hydro-mechanical modelling of hydraulic field tests combined with fracture displacement measurements (Cappa et al., 2006; Cappa et al., 2008). These studies, however, were not extended to borehole stability problems and were more inclined towards rock mass characterization. Furthermore, simulating and monitoring these coupled processes in-situ and developing relationship between them remain a major challenge. Rock failure can occur as a result of rock strength anisotropy caused by weak bedding planes and natural fractures. In these cases, increased mud pressure can further deteriorate the situation by mud loss (Santarelli et al., 1992). Modelling of such a geologic environment presents many challenges and requires analysing operational parameters and in-situ stress conditions.

Numerical methods have been used extensively to perform stress analyses and to evaluate stability of underground excavations in jointed rock masses by incorporating discontinuities explicitly. The Finite Element Method has been used frequently to simulate continuous medium (Zhang and Roegeirs, 2005; Salehi et al., 2010) and occasionally discontinuous material (Helstrup et al., 2004). However, their formulation is usually restricted when intersecting interfaces are encountered or if they are recognized, their formulation is limited to small rotation (Itasca, 2013). DEM models the rock mass is modelled as an assemblage of rigid or deformable blocks. Discontinuities are considered as distinct boundary interactions between these blocks.

DEM has been used in research programs associated with geological disposal of nuclear waste (Cappa et al., 2006, Min et al., 2004), stress field modelling (Brady et al., 2003; Su, 2003; Stephanson, 1999; Hart, 2003), hydraulic fracturing in rocks with minimal permeability (Nagel et al., 2011), stress dependant permeability (Min et al., 2004), geometric and hydraulic properties of fractured medium (Wei et al., 2017)stability of underground excavations (Bhasin and Høeg, 1998; Sapigini et al., 2003) and proves to be a vital tool in understanding rock failure mechanisms in jointed rock mass and borehole stability in fractured rock mass (Zhang et al., 1999). In fractured rock mass with low or none matrix permeability fluid flow occurs through fractures which essentially means closure of fracture and shear dilation will be main parameters affecting the stability near excavation. Fluid flow in fractures have been studied by parallel plate model following cubic law. However, there are few studies that suggest when flow rate and viscosity are higher, fluid flow is non-linear and cubic law may overestimate fluid conductivity (Yu et al., 2017).

Zhang et al. (1999) studied borehole stability by measuring displacement and estimating stresses around the excavation. In a borehole intersecting fractured rock medium, borehole collapse has been explained by invasion of mud into the fractures. The invasion of mud increases the pore pressure therefore reducing the effective normal stress. A shear release then results in lateral displacement at the fracture plane. However, in underbalanced conditions where mud invasion is unlikely, predominant failure mechanisms are induced by stress concentration and back flow of fluid. There are very limited studies investigating borehole stability in fractured rocks under pore pressure and drilling fluid. As a result, in this study, a 3DEC based hydro-mechanical model is developed to investigate stability of a borehole being drilled in fractured rock mass.

In this study, DEM based code 3DEC is used to investigate borehole stability and simulate the pore pressure being generated in rock mass due to presence of underground water and also study effect of mud pressure on borehole stability. In doing so, a vertical borehole drilled in a rock mass with explicitly defined discontinuities in Perth basin was modelled. Firstly, a layered model of Mountain Bridge (MB-1) borehole is generated and then the yield zone around the borehole is validated against caliper log measurements.

Since Carynginia formation in the northern Perth basin is considered to be one of the most prolific shale gas target, subsequently parameters that may affect stability in this region are evaluated. Therefore, by undertaking sensitivity study, influence of fluid flow rate in the borehole and fluid viscosity on borehole stability is investigated at monitoring points around the borehole.

3.3 Borehole stability in Perth basin

Perth basin is located in southern Western Australia. It is a north-south trending rift basin extending about 1000 km from north to south. North-South trending darling fault which dips steeply (approximately 70°) is located on the east of the basin (King et al., 2008). It has been interpreted that faults in the Perth basin are a result of series of geological events and follow the present-day stress regime. Because of intense tectonic evolution, Perth basin have sets of fractures aligned with faults generated during a specific tectonic episode.

One of the first dedicated shale gas well of Western Australia, Arrowsmith-2 was drilled in the Perth basin. However, drilling in the shale is often associated with problems such as tight holes and drill stuck. Rasouli and Sutherland (2014) presented log based rock mechanical model to characterize shale properties to overcome wellbore instabilities. While analysing data from Caliper log, Rasouli and Sutherland (2014) found indications of wash out and enlarged breakouts which gives us the idea of instabilities present in that particular region. It is apparent from King et al. (2008), Rasouli et al. (2013) and Rasouli and Sutherland (2014) that the problem of borehole instability in Perth basin is because of combination of rock properties and presence of fracture sets aligned with tectonic episodes. To investigate this issue, in this study DEM is implemented, firstly, models of four rock formations encountered in MB-1 are simulated and compared with caliper log. Secondly, to investigate effect of fracture on borehole stability, borehole flow of fluid and viscosity of fluid is analysed.

3.4 Discrete Element Modelling

Naturally fractured rocks are traditionally treated as dual porosity media. Primary porosity generated during diagenesis and secondary porosity as a result of faulting and related tectonic processes (Zhang et al., 2003). Rocks like shale may have primary porosity but permeability is negligible in these rocks. Therefore, dominant mechanism of fluid flow in rocks is through fissures and fractures. When deformation of solid material is key for analysis, rock blocks can be divided into finite elements to increase the degree of freedom. These deformable blocks are modelled using Mohr-Coulomb failure criterion which allows rocks blocks to deform plastically.

In this model generated by 3DEC, the deformation of plastic deformation is restricted to intact rock blocks. 3DEC code has the ability to perform fully coupled hydro-mechanical analyses which enables researchers to investigate the relation between deformation of rock mass and hydraulic conductivity of a block system. In this case, the flow is governed by pressure differential between adjacent domains.

3.4.1 Model geometry

In the numerical analyses conducted herein, problem domain presented as a 5 x 5 meter block. A circular vertical borehole is drilled near the fault with a diameter of 0.15 m. Two sets of fractures that are present in the basin are reproduced in the model as fracture set 1 (F1) runs east-west while fracture set 2 (F2) is present in North northwest direction and can be observed in a planar view of the model presented in Fig. 3.1a. The two sets of fractures have moderate to high dips (King et al., 2008). Therefore, average dip of 45° is used for both fracture sets. To achieve continuous history of measurement five measuring points are placed around the wellbore. Location of three measurement points (1-3) along x-axis and positive y-axis are shown in Fig. 3.1b. Points 1 and 3 are located on x-axis on either side of the borehole while points 2 and 4 located on y-axis opposite to each other, Point 5 is considered as a comparison location and is located a bit further away from the borehole on the x-axis to observe and compare background parameters of the borehole. In this respect, points 1 to 4 are placed around borehole within radius of 10 cm of borehole walls whereas point 5 was placed at 50 cm on the positive x-axis.

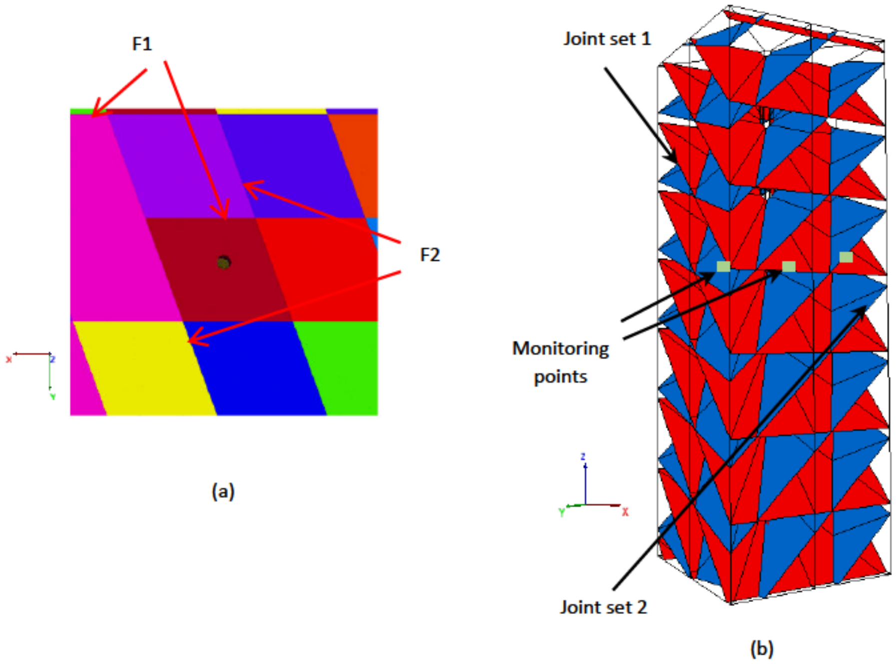


Figure 3.1. (a) Planar view of 3DEC model with a borehole in the centre and two sets of fracture in the rock mass. (b) Model geometry of model with two fracture sets and an intersecting borehole

3.4.2 Boundary conditions

The problem domain is considered to be in a deep-seated environment with a vertical stress gradient of 21.5 MPa/km. Therefore, a constant load (σ_v) equivalent of overburden rock mass is inserted using following relation:

$$S_v = \int_{Surface}^{TVD} \rho g dh \tag{3.1}$$

Where, TVD is true vertical depth, ρ is the density of overlying strata, g is the acceleration due to gravity and *dh* is the change in height.

Similarly, major and minor horizontal stresses (σ_H and σ_h) are aligned with x-axis and y-axis respectively. Rasouli and Sutherland (2013) estimated magnitude of S_H and S_h. These magnitudes were used to calculate the ratio of S_H and S_h in relation to S_v which were estimated as 0.818 and 0.788 respectively. These ratios were then used to apply horizontal stress gradients for the base case according to following relations:

$$S_{xx} = K_H * S_{zz} \tag{3.2}$$

$$S_{yy} = K_h * S_{zz} \tag{3.3}$$

Initial pore pressure (P_p) in the borehole, associated with groundwater pressures is assumed to be 10.1 MPa/km. Boundary conditions of the model generated are tabulated in Table 3.1. The bottom boundary of the model is fixed as null displacement. A schematic representation of model boundary conditions and borehole is presented in Fig. 3.2.

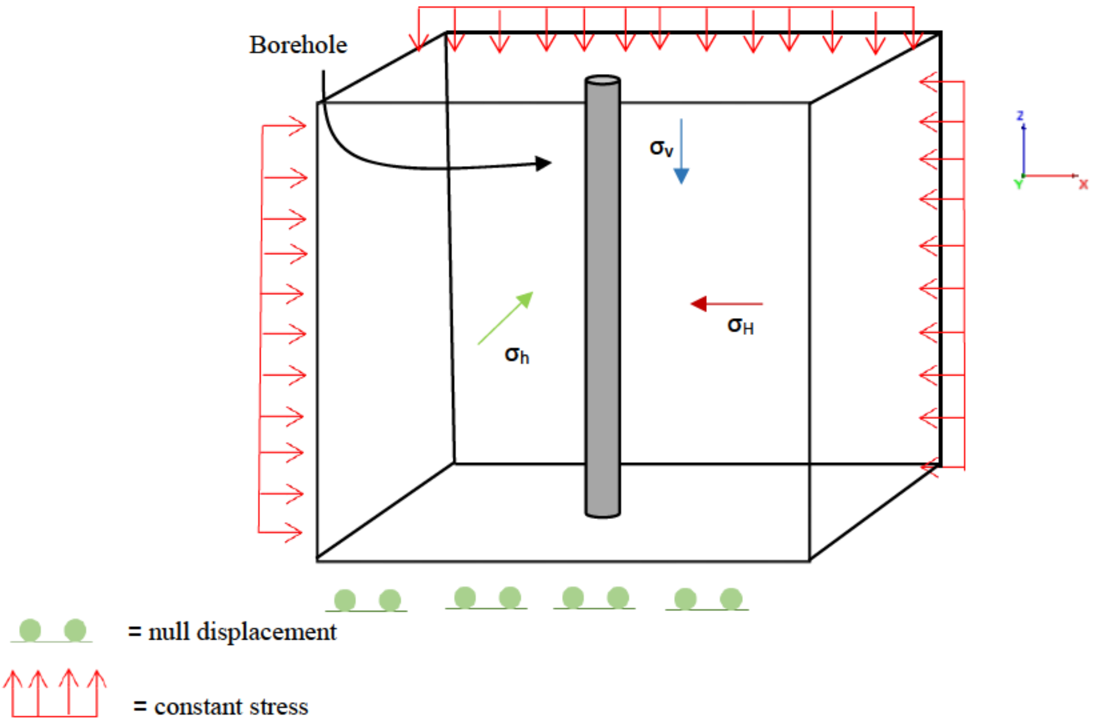


Figure 3.2. Schematic representation of boundary stresses applied to the model

Table 3.1. Boundary conditions of model presented as gradients

Insitu stress and pressure	
Maximum Horizontal Stress σ_H (MPa/km)	21.5
Minimum Horizontal Stress σ_h (MPa/km)	20.6
Vertical Stress σ_v (MPa/km)	26.2
Pore pressure (MPa/km)	10.1

3.4.3 Rock mass constitutive relations

The numerical model is generated by assemblage of distinct blocks which are further divided into deformable triangular finite difference zones. Each zone has its own mass and act as a single entity. Discontinuities between the blocks act as boundaries. The amount of normal and shear displacement between two blocks can generally be determined from the translation and rotation of centroid of each block. Therefore, normal and shear force increments are related to incremental relative displacements as presented in below expressions:

$$\Delta\sigma_n = K_n \, \Delta\mu_n \qquad (3.4)$$

$$\Delta\tau_s = K_s \Delta\mu_s \qquad (3.5)$$

Where, K_n and K_s are normal and shear stiffness of the contact, $\Delta\sigma_n$ and $\Delta\tau_s$ are effective normal and shear stress increments, and $\Delta\mu_n$ and $\Delta\mu_s$ are normal and shear displacement increments.

Intact rock block in between fractures is modelled as Mohr-Coulomb material and subdivided with a mesh of constant strain triangular finite difference elements. Shear behaviour of the fracture is modelled as Mohr Coulomb slip model where shear stress (τ_s) is limited by combination of cohesion (C) and friction angle (ϕ) following the Coulomb failure criterion expressed in equation 6. As normal stress (σ_n) is changed because of fluid movement, effective normal stress (σ'_n) aid in shear failure at the discontinuity.

$$\tau_s \leq C + \sigma'_n \tan\phi \tag{3.6}$$

Where, τ_s is shear stress, σ'_n is effective normal stress, C is cohesion and ϕ is friction angle. In this study, the results of DEM were validated against field data. Therefore, it was required to select a constitutive model which input parameters can be adopted from the literature. As a result, Mohr-Coulomb model is adopted.

3.4.4 Fracture fluid flow

In a natural fracture, fluid occurs through interconnected voids between two rock surfaces in partial contact. Fluid flow is maximum through those channels that have large apertures and minimum through those fractures that have smaller apertures (Zimmerman et al., 1992). As a first approximation, the fluid flow between two fractures is modelled as flow between two parallel plates called "parallel plate model" with a constant hydraulic aperture (b_h) explained by "cubic law" (Cappa et al., 2008) by the following equation:

$$q = \frac{b_h^3 w \rho g}{12\mu} \Delta H \tag{3.7}$$

Where, q is the flow rate, w is the fracture width and ΔH is the hydraulic head gradient, b_h is the hydraulic aperture, ρ is the fluid density, g is the gravitational constant and μ is the fluid viscosity.

3.5 Borehole stability modelling

3.5.1 Model validation using field data

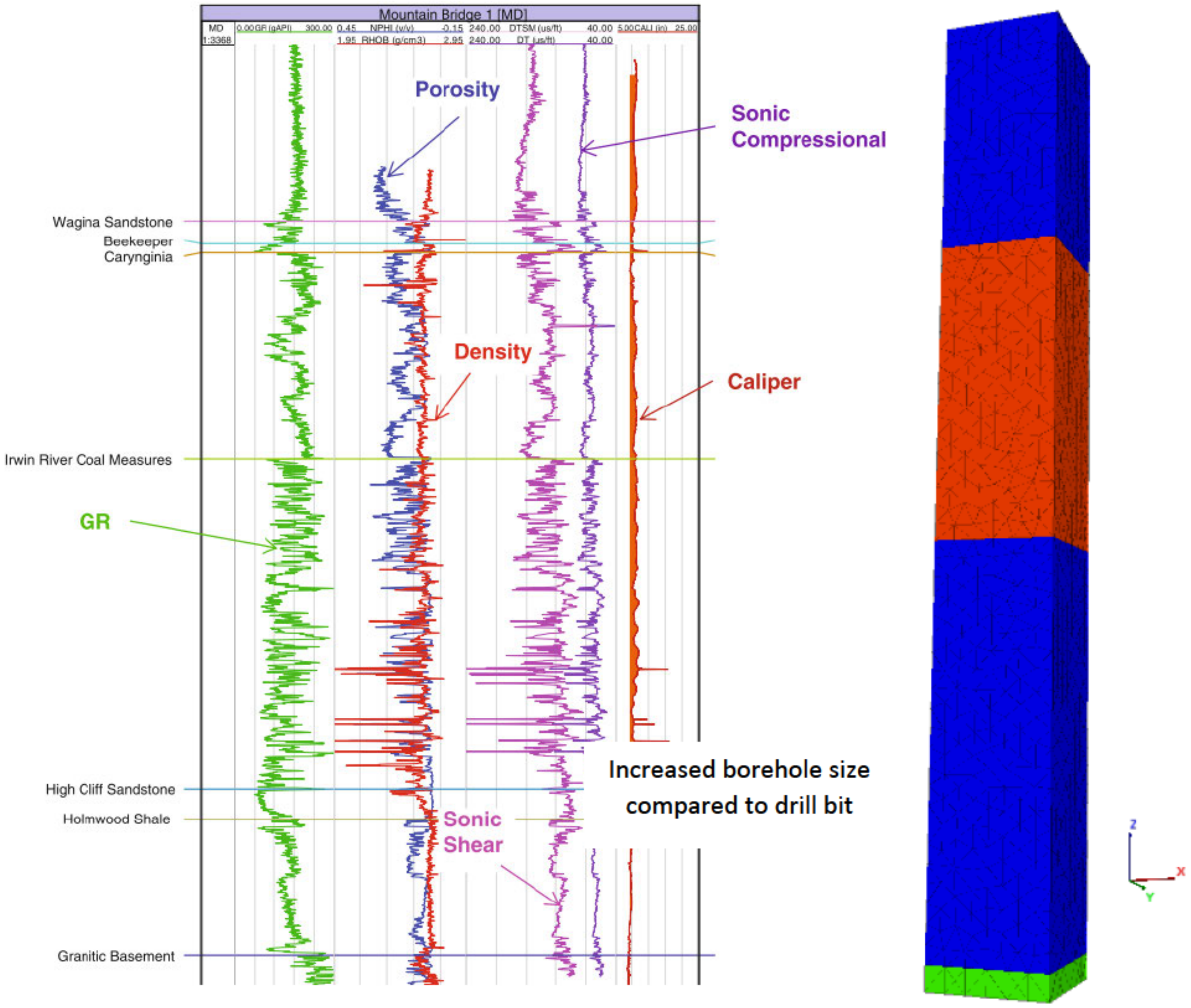
A numerical model of borehole stability in Northern Perth basin is generated and then field data is used to validate the model. Rasouli and Sutherland (2013) utilized geological and petrophysical logs to generate a rock mechanical model (RMM) to analyse stability around Arrowsmith-2 (AS-2) and Mountain bridge-1 (MB-1) wells. In this study, stability condition of MB-1 which is a problematic borehole is investigated as a base case. To generate a numerical model, rock properties associated with MB-1 wellbore are extracted from Rasouli and Sutherland (2013) and tabulated in table 3.2.

Table 3.2. Modelling properties for Northern Perth basin

Lithologies	Intact rock properties	Values
Kockatea Shale	Density (kg/m^3)	2650
	Bulk modulus (GPa)	14.16
	Shear modulus (GPa)	6.53
	Friction angle (degree)	24
	Cohesion (MPa)	0.55
	Dilation angle (degree)	0
	Tensile strength (MPa)	5.3
Carynginia formation (Sandy Shale)	Density (kg/m^3)	2600
	Bulk modulus (GPa)	20.90
	Shear modulus(GPa)	10.78
	Friction angle (degree)	28
	Cohesion (MPa)	0.55
	Dilation angle (degree)	0
	Tensile strength (MPa)	8.0
Irwin river (Coal)	Density (kg/m^3)	2580
	Bulk modulus (GPa)	18.18
	Shear modulus(GPa)	9.38
	Friction angle (degree)	24
	Cohesion (MPa)	3.55
	Dilation angle (degree)	4
	Tensile strength (MPa)	1
High Cliff Sandstone	Density (kg/m^3)	2550
	Bulk modulus (GPa)	30.55
	Shear modulus(GPa)	22.91
	Friction angle (degree)	46
	Cohesion (MPa)	13
	Dilation angle (degree)	11.5
	Tensile strength (MPa)	10.7
	Fracture properties	

	Normal stiffness (GPa)	9
	Shear stiffness (GPa)	6
	Cohesion (MPa)	0
	Friction angle (degree)	32
	Residual aperture (m)	1.25e-4
	Zero normal stress aperture (m)	2.5e-4

Analysis using yielded zone around the borehole has been carried out against the caliper log to define the overall condition of borehole after drilling. Ideally a stable borehole would be of same diameter as of the drill bit, however, in practice, the borehole is either larger than the drill bit (because of rock breakage and splintering) or smaller (because of swelling of clay minerals, particularly in shale). Caliper log gauges the size of the hole and indicates failure in form of increased borehole size. Fig. 3.3a presents different log runs carried out in the borehole MB-1 from 2500 meters to 3300 meters depth. Caliper log in the same figure clearly shows that the size of the borehole changes as a new formation is encountered. This observation indicates that rock properties are playing a vital role in the stability of borehole. A layered numerical model of MB-1 from depth 2500 to 3300 meters is presented in Fig. 3.3b. The layered model is simulated to determine the thickness of a single layered model and regulate any boundary effects between two rock formations. King et al. (2008) measured in-situ stress and fracture orientation across northern Perth basin using a number of image log data sets. The authors presented maximum values for principal stresses at 1 km which are used in this study as stress gradient for validation of numerical model. Principal stresses and pore pressure values used in this model are tabulated in table 3.1 while rock mass properties for each rock layer are listed in table 3.2. Furthermore, to reduce computation time of the model, each rock formation was simulated separately with a preferred vertical depth to avoid boundary effects. Then stability was assessed separately by analysing deformation around borehole and the effect of discontinuities was assessed by measuring shear displacement at monitoring points placed strategically on fracture planes.



(a) (b)

Figure 3.3 Mountain bridge-1 (MB-1) well drilled in Northern Perth basin (a) Petrophysical logs (b) Layered model of from 2500m to 3300m

The way in which a borehole responds to the drilling operation is dependent on the complex geological structures, far field and local stresses and operational parameters. Therefore, to define whether a borehole is stable or not, it is not possible to determine a definite threshold of deformation of rock blocks for a particular condition. In this study hydro-mechancial coupling simulation in rock fractures around a borehole is carried out to analyse instabilities that generate along fractures and affect the borehole stability in a fractured rock mass. It is assumed that some degree of disturbance will be a common practice in the wells with fractured rock medium. To simulate borehole conditions, fluid pressure of 11 MPa/km was used to pressurize the borehole. In-situ stress and pore pressure values are tabulated in Table 3.1 whereas rock and fracture properties are presented in Table 3.2. Contingent on the pore pressure and magnitude of in-situ stress fluid then penetrates into discontinuities. Fluid flow is calculated using classical cubic law based on the parallel plate model. The hydraulic aperture, Bh, of the discontinuity at a given normal stress is updated according to its mechanical normal displacement variation, ΔUn. In 3DEC, blocks are impermeable, therefore, fluid flow occurs only in discrete discontinuities.

To investigate borehole stability, initially the model is run as a base case. Mechanical boundary is applied at the borehole to observe the plastic zone which is a significant indication of rocks being deformed around the borehole. 3DEC has the ability to plot the plastic flow of material but rather than actual flow it indicates yielding of the blocks and can be determined by blocks remaining in place. The failure mechanism is indicated by yielding of the blocks. Initial yielding occurs at the start of simulation indicating unbalanced system. As the simulation progresses stresses redistribute themselves and unloads yielding elements so that the stresses no longer satisfy the yielding criterion. Such elements are termed as “yielded in past” and indicated in Fig. 3.4 by –p. Active yielding elements at the end of simulation are termed as “yielding now” and shown as –n in Fig. 3.4. Elements yielded in the past and yielding now together define the plastic zone around the borehole (Itasca 2013).

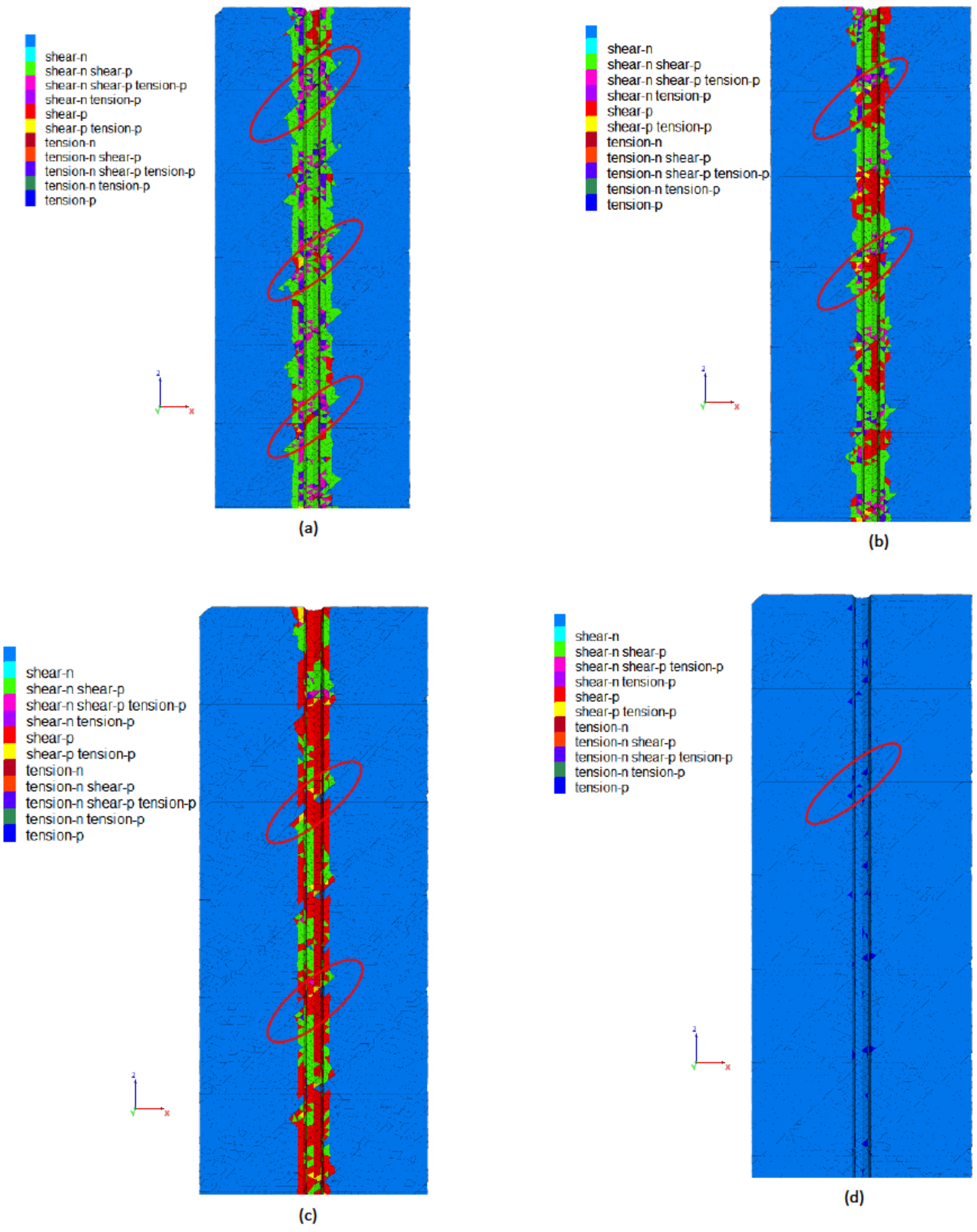


Figure 3.4. Yielded zones around borehole for each rock formation (a) Kockatea shale (b) Caryngia formation (c) Irwin river (d) High Cliff Sandstone

Fig. 3.4 shows the development of yielded zone around borehole for four rock formations investigated in this study. The amount of yielding is measured to define the deformation around the borehole. Fig. 3.4 demonstrates that instability is very sensitive to lithology. The model of High cliff sandstone shows no apparent deformation apart from minor yielding element that can be seen along discontinuity plane. However, the borehole being drilled in Kockatea shale has experienced large yielding and therefore instability. There are considerable yielded areas in the borehole being drilled in Caryngінia formation and Irwin river. In general, stronger materials, in this case High Cliff sandstone, show minimal deformation while weaker material such as Kockatea Shale and Caryngінia formation show significant yielded zone development. Fig. 3.4 presents another mechanism of deformation that is observed in each model which is the area around discontinuity plane is subjected to large amount of deformation. These deformation zones are circled and are further analysed to investigate instability. This simulated deformation for each rock formation is compared to caliper log of MB-1 (Fig. 3.3a) in Fig. 3.5. Fig. 3.5 demonstrates the area of borehole became unstable at specified depth for each formation. R is the unstable radius, whereas, r_w is borehole radius. In this figure, graph named as "Measurement" shows the Yielded zone which is obtained by the caliper log measurement. "Base case" graph demonstrates the yielded zone obtained by numerical modelling. Each formation was simulated subjected to hydro–mechanical modelling. It may be seen that there is a good agreement between field measurement and simulation results, therefore, the method practised in this study is relevant to estimate borehole stability in fractured rock.

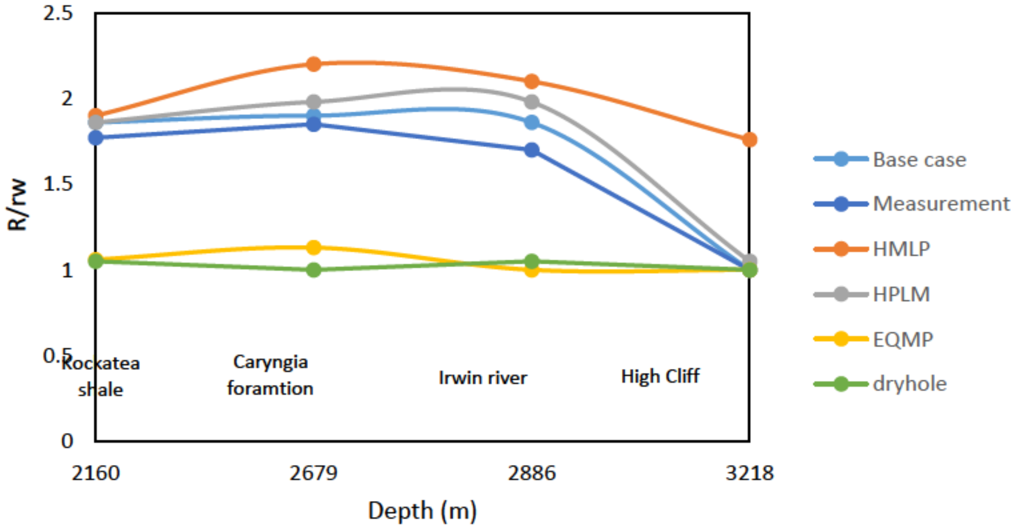


Figure 3.5. Comparision between DEM simulation and measured results, yield zone measurement for each formation and simulated cases

3.5.2 Shear displacement assessment

When an underground excavation is carried out, a number of hydro-mechanical processes occurs. As explained earlier, redistribution of stress field around the system occurs which in turn change fracture aperture affecting pore pressure and permeability. In case of a pressurized borehole, fluid penetrates into fractures and can cause shear failure by reducing the effective normal stress acting on the fractures around borehole not only changes because of mechanical redistribution of stresses but also because of modification of pore pressure in the fracture. This is further explained in the next section.

To analyse the impact of fractures and discontinuities on stability of the borehole, shear displacement was monitored and extracted from the simulation. The results are presented in Fig. 3.6. As mentioned earlier, five monitoring points were used in this study to measure shear failure and pore pressure changes influenced by mud penetration. As mentioned in the previous section, parallel plate model measure displacement at these monitoring points. Points 1 and 3 are placed along x-axis 15 cm away from the centre of the borehole. Similarly, point 2 and 4 are placed along y-axis at the same distance from the centre of the borehole. These monitoring points are strategically placed at discontinuity planes to measure slightest change in shear displacement and fluid pressure. Whereas, point 5 is used to monitor background pore pressure and therefore is placed 50 cm on the positive x –axis. This helped us to observe and compare dramatic variations given the size of the model.

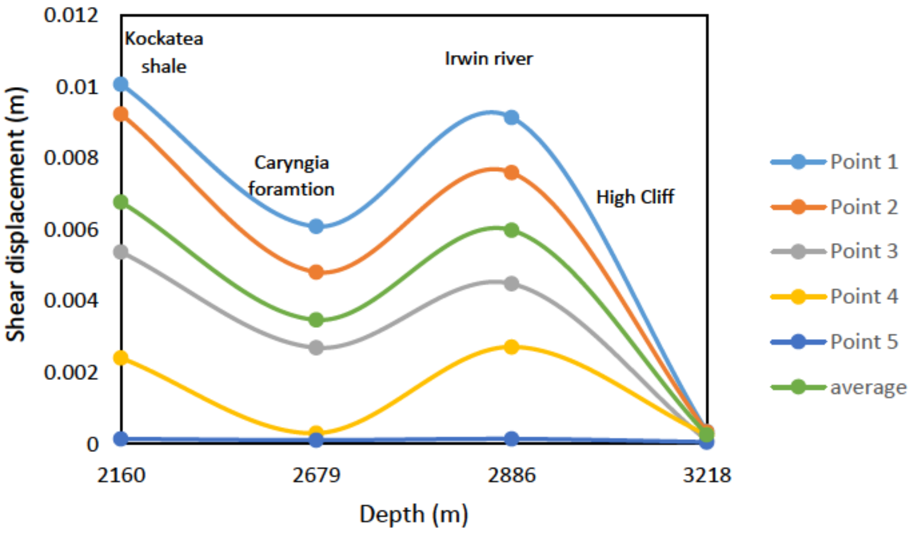


Figure 3.6. shear displacement simulation results for each formation

Fig. 3.6 represents shear displacement at monitoring for each rock formation. It can be interpreted from Fig. 3.6 that shear displacement at High cliff sandstone contact is near zero as compare to other rock formations. This is mainly because of the strength of rock which is considerably high compared to the other rock formations which inhibits movement along fractures. The behaviour of High cliff sandstone can be correlated with yield zone radius graph in Fig. 3.5. Furthermore, an average of shear displacement for points 1 to 4 was calculated. It was observed that Kockatea shale had an average shear displacement of 0.0067 m which is the highest shear displacement among all rock formations. Consequently, Irwin river had a shear displacement of 0.006m and Caryngnia formation had shear displacement of 0.0034m. It is observed that whether the borehole is simulated with or without mud influx, stability around borehole is highly dependent on rock properties.

3.5.3 Mud pressure and pore pressure equilibrium

A borehole in the subsurface provides access to the reservoir which is seated hundreds of meters below. The borehole intersects a number of rock formations and discontinuities in the form of small scale fractures and large-scale faults. These planes of weaknesses have the potential to slide as soon as they are drilled into and mud infiltrates in it.

Fracture sliding initiates as the induced shear stress applied on a given plane inside the rock mass exceeds the shear strength along that plane. Formations are usually inhomogeneous and anisotropic hence sliding tends to take place along the weakest plane within the rock mass.

Fracture sliding may occur in three different stages during the life of a borehole: fracture sliding during drilling operation, sliding during production from the reservoir and sliding during injection (hydraulic fracturing) to increase permeability and drainage area of the reservoir. The mechanism of sliding in each of these cases is different and is vital to understand.

Therefore, after validation of 3D DEM approach adopted in this study, hydro-mechanical simulation of each is carried out to investigate the effect of balance between mud pressure and pore pressure. In doing so, different cases which were HMLP (high mud pressure, low pore pressure), HPLM (high pore pressure low mud pressure), EQMP (equal pressure for mud and pore pressure) and dry hole (zero mud and pore pressure) were investigated. Fig. 3.7 represent the mechanism of HPLM, HMLP and EQMP schematically. A fully coupled hydro-mechanical analysis was performed in which hydraulic conductivity is dependent on the mechanical displacement of discontinuities and deformation of intact rock.

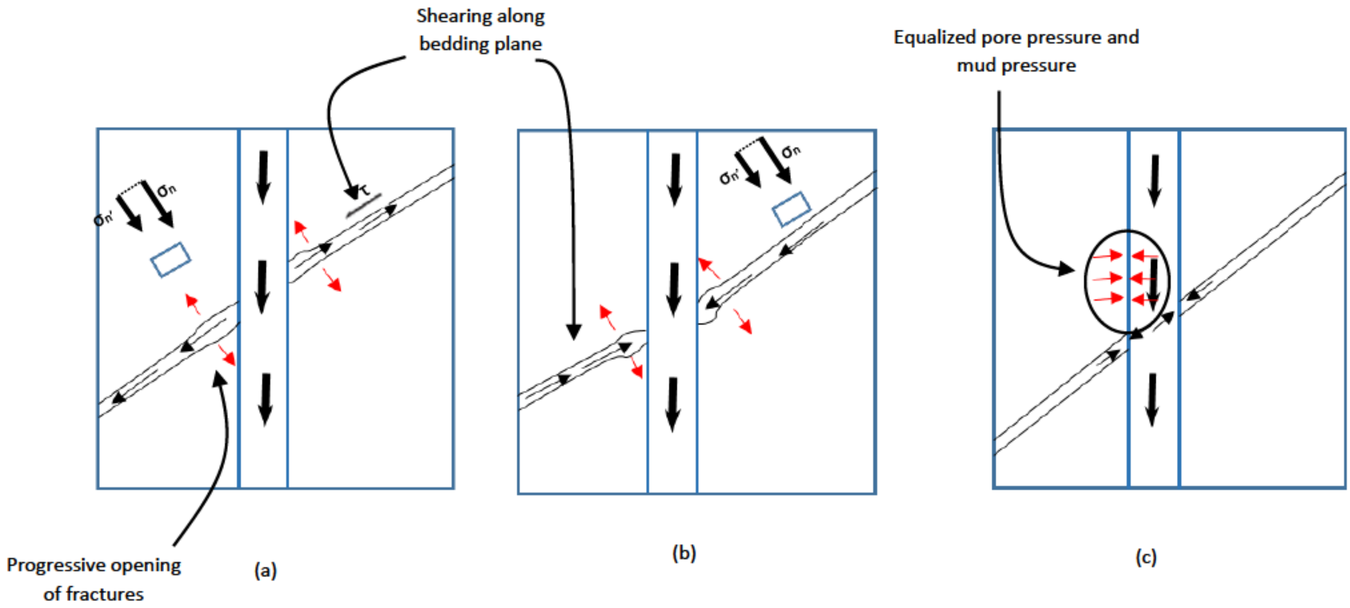


Figure 3.7. Schematic representation of fluid penetration in fractures (a) HMLP (b)HPLM (c) EQMP

The objective of these simulations is to better understand the importance and role of fluid flow in borehole instability when simulating fracture inflow into an underground excavation. First of all, yielded zone is analysed for each formation and compared to the base case simulation in Fig. 3.5.

In general, depending on the value of pore pressure and mud pressure inside the borehole four different situations may happen in the borehole being drilled in fractured rock mass:

a) In most of cases, the amount of mud pressure is more than the pore pressure. Therefore, drilling fluid infiltrates into a discontinuity that is intersected by a borehole. As a result, the fluid pressure along the fracture plane will increase. As demonstrated in Fig. 3.7a this phenomenon will lead to the reduction of effective normal stress, therefore, a reduction in shear strength. According to Mohr-Coulomb failure criteria presented in Equation 6, the new state of stress may exceed the joint shear strength and cause sliding of joints as presented in Fig. 3.7a. Fig. 3.5 shows that the case of HMLP (i.e. high mud pressure and low pore pressure) in which mud pressure significantly exceeds pore pressure, is the most unstable case. Even High cliff sandstone model has a yield zone value of 1.76 compared to other models where mud pressure is considerably low. This is mainly because high flow rate tends to penetrate deep into fractures and open up the aperture if pore pressure is very low. In this case, due to an increase in hydraulic aperture, and a decrease in effective normal stress, the yielded zone and shear displacement increases. The results are consistent with the study undertaken by Santarelli et al. (1992) who showed that high mud pressures in fractured rocks increase the instability. This type of failure is the most common in drilling boreholes intersecting naturally fractured rocks.

b) The second case, which is when pore pressure is higher than mud pressure, is common when the borehole is drilled to produce mineral resources from a reservoir. To produce gas and oil from the reservoir the mud pressure is reduced to allow hydrocarbons to flow from rock matrix and naturally occurring fractures to the borehole. Similar to the previous case, as demonstrated in Fig. 3.7b, the high flow of fluids increases the pore pressure around the borehole which in turn reduces the effective normal stress and therefore trigger shear failure along the discontinuities.

The results presented in Fig. 3.5 for HPLM, which is the case when mud pressure is negligible and pore pressure is significantly high, shows that flow direction is from subsurface towards the borehole and a yield zone is formed which is smaller in diameter than HMLP but larger than the base case indicating high instability. As demonstrated in Fig. 3.7b when the pore pressure exceeds the mud pressure, the formation water tends to move from sub surface towards the borehole resulting in yielding and shearing along discontinuities. HPLM model for each rock formation simulated in Fig. 3.5 shows the yield zone radius is higher when compared to base case but lower than HMLP models. HPLM graph line followed the same trend as base case and HMLP.

c) The third condition is schematically demonstrated in Fig. 3.7c. In this condition mud pressure balances out pore pressure (i.e. EQMP), therefore, no extra fluid pressure will be generated in the fractures. As demonstrated in Fig. 3.5 for EQMP results, this condition is almost the most stable condition. All formations with EQMP conditions have a value of 1.0 for R/rw except Carynginia formation which has a yield zone radius of 1.13.

As can be seen in Fig. 3.5 similar results are obtained when simulating a dry borehole, in which no pore pressure or mud pressure are generated. A very minor deflection of deformation is observed for the model of Carynginia formation, otherwise the R/rw values are equal to 1.0.

The results show that the balance between pore pressure and mud pressure plays significant role in stability of a borehole being drilled in a fractured rock mass. Therefore, in an ideal case the total pressure applied to the borehole wall is equal to the pore pressure in the subsurface. It prevents any infiltration of fluid into the subsurface and also prevents uncontrolled flow of the well specially when dealing with a gas well. However, maintaining balance between mud pressure and pore pressure may not be achievable in field condition.

3.6 Parametric Study

The modelling aims to simulate hydro-mechanical behaviour of fractured rock mass to simulate mud pressure applied in a borehole. In doing so, shear displacements and fluid pressure along discontinuities at the five observation points, introduced earlier, were investigated.

Since the input parameters exhibit wide impact on the behaviour of discontinuities, the model of Carynginia formation is used as a reference for the parametric study to investigate the effect of each of the parameters on the hydro-mechanical behaviour of the discontinuities network. Model of Carynginia formation simulated is therefore used to carry out a parametric study to investigate effects of fluid flow rate in the borehole and viscosity of fluid on shear displacement and fluid pressure in the rock mass around the borehole. Matrix and fracture properties of Carynginia formation are presented in Table 3.2. In-situ stresses and pore pressure are simulated as gradients which are tabulated in Table 3.1. Precise magnitude of these properties can be estimated using relations presented in equation 1 and 2. Fluid pressure of 11 MPa/km was used to pressurize the borehole.

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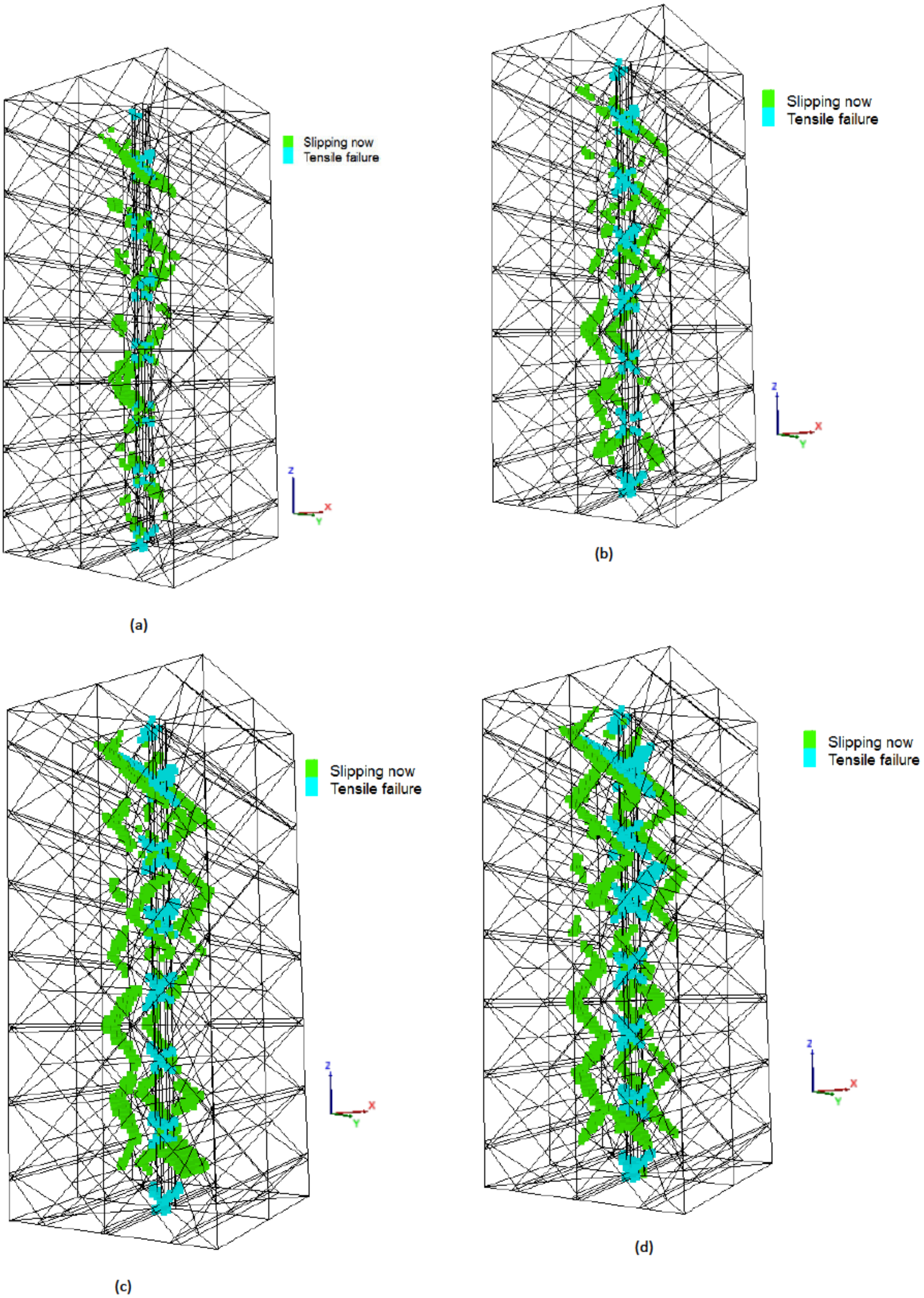
3.6.1 Effect of Mud flow rate

To investigate effect of mud flow rate on borehole stability, different flow rates of 20, 40, 60 and 80 barrels per minute (BPM) were applied and its effect of tensile and shear failure around the borehole, shear displacement and fluid pressure in discontinuities was evaluated. For the model simulated here, as shown in Fig. 3.8, a constant increase in shear displacement along discontinuities is observed as the flow rate increases. Blue dots in Fig. 3.8 represent tensile failure as a result of fluid penetration while green dots named ‘slipping now’ represent shear failure at the current stage of the model. The mechanism of failure can be observed in Fig. 3.7a. As the flow rate in the borehole is increased, mud starts to penetrate into fractures decreasing normal stress of the discontinuity. As a result, shear displacement is experienced along the discontinuity. Similarly, increasing borehole pressure increases tensile stress resulting in tensile failure.



(a) (b) (c) (d)

Figure 3.8. Tensile failure and shear displacement along fractures for (a) 20 BPM (b) 40 BPM (c) 60 BPM (d) 80 BPM

The above discussion is well presented by Fig. 3.9a. The shear displacement at monitoring points are minimum when the flow rate is 20 BPM. Shear displacement then increase with an increase in flow rate.

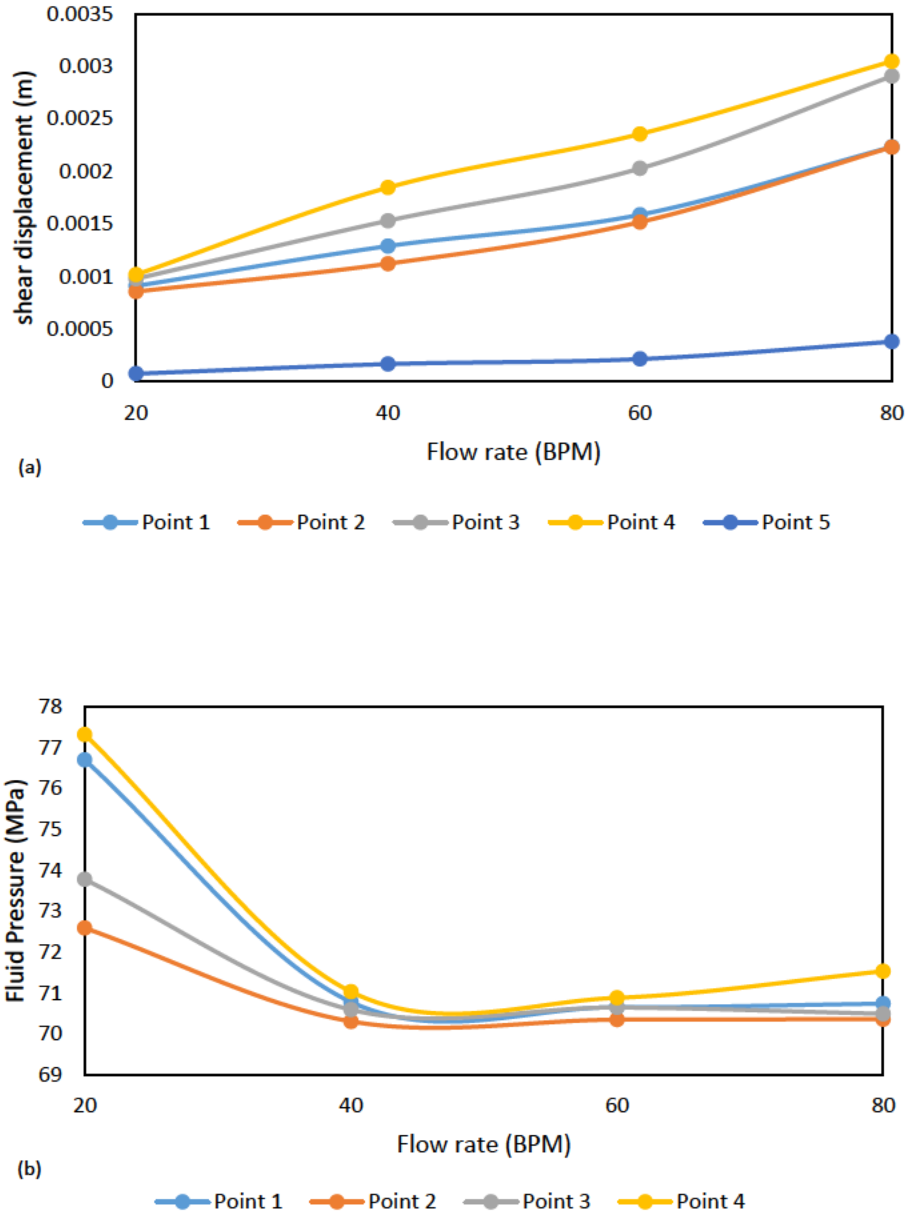
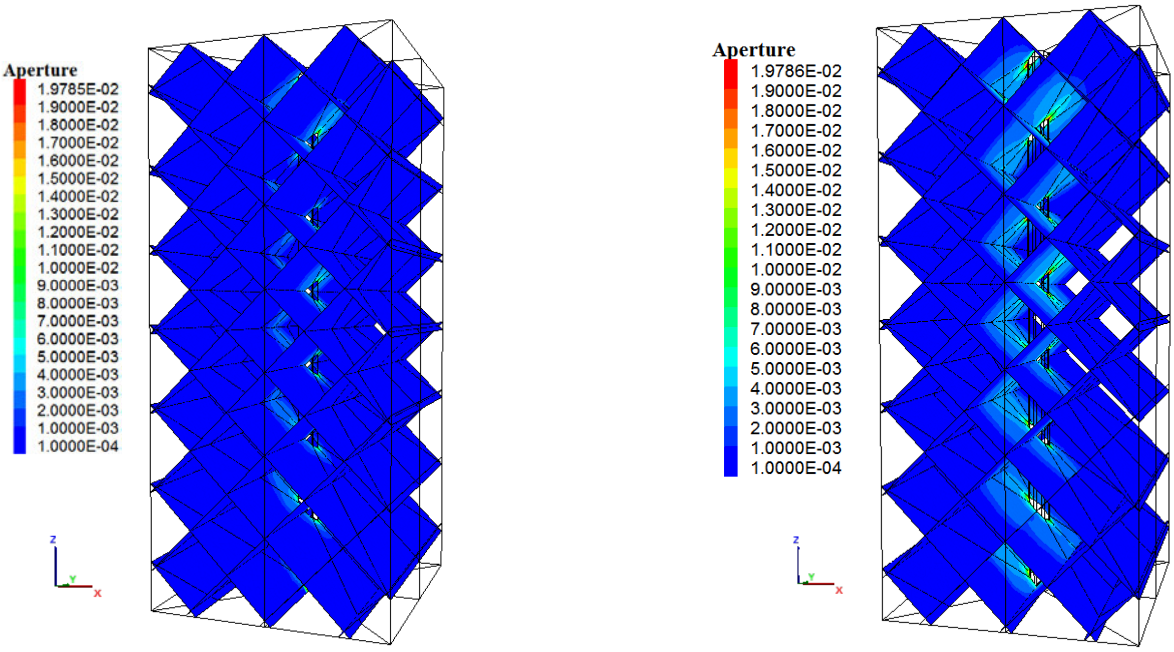


Figure 3.9. Effect of flow rate on simulation results at monitoring points: (a) Shear displacement (b) Fluid pressure

Fig. 3.9b shows fluid pressure at each monitoring point for different flow rates. When the flow rate was kept at 20 BPM, the in-situ pore pressure values at different monitoring points are the maximum values. This is mainly due to low shear displacement happens at this low fluid rate (see Fig. 3.9a), therefore, the hydraulic aperture is not large enough to allow unrestricted fluid flow, as the flow rate is too low to generate tensile failure. As a result, pore pressure dissipation is slow, which will result in fluid pressure build up. Increase in mud flow rate will generate tensile failure and therefore enhance pore pressure dissipation, therefore, fluid pressure drops and then stays constant. This discussion is confirmed with the models presented in Fig. 3.10 showing Hydraulic aperture plots for 20 BPM and 80 BPM models. As can be seen in this figure hydraulic aperture is larger when fluid flow is higher. With larger aperture pressure can be released easier and therefore lower pressure is observed when fluid flow rate is larger.

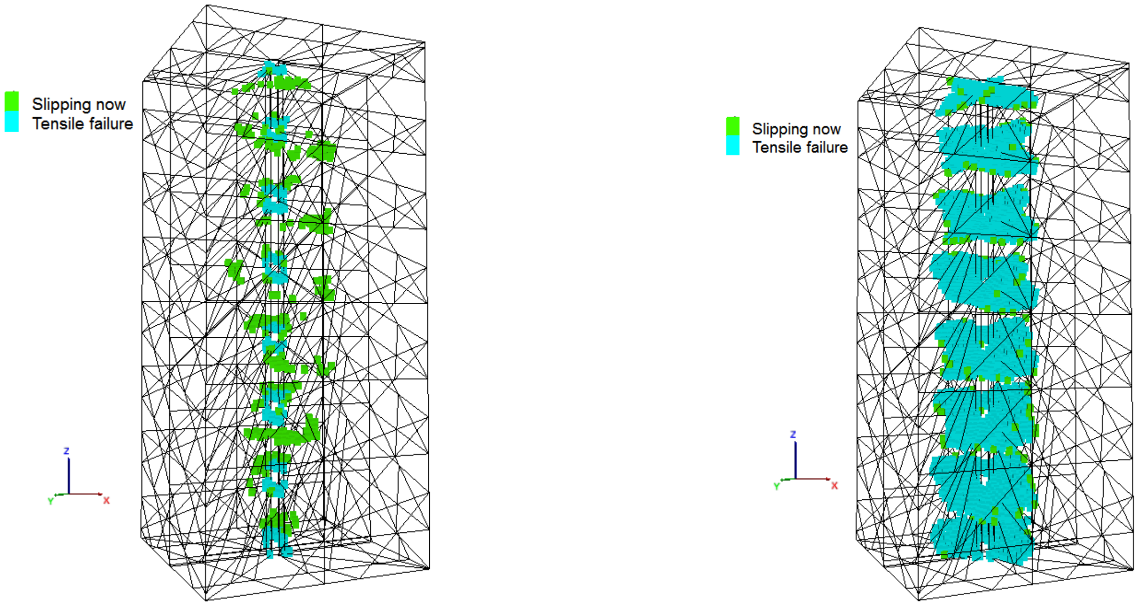


(a) (b)

Figure 3.10. Hydraulic aperture distribution along discontinuities for (a) 20 BPM (b) 80 BPM

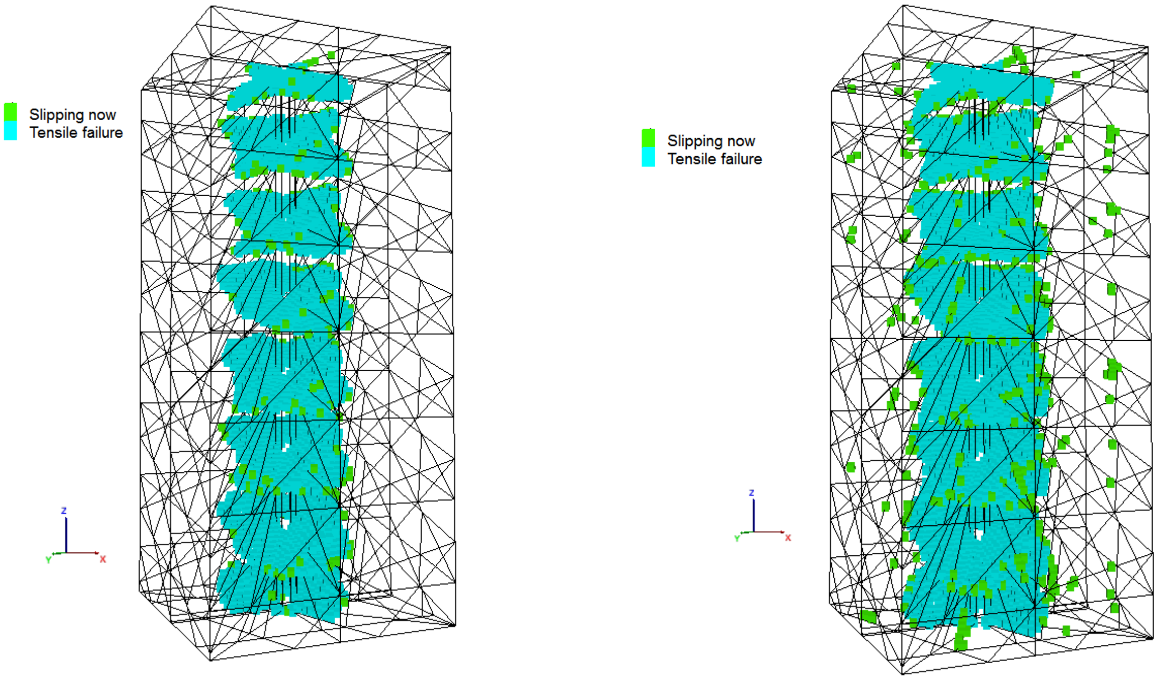
3.6.2 Effect of Viscosity

It is important to know effect of drilling fluid viscosity on the stability of borehole. Nagel et al. (2013) simulated a hydraulic fracturing model with a specified friction angle for naturally fractured rocks. Their results indicate that that fluid viscosity can have a significant influence on microseismic events and recommend that fluid injection model should be thoroughly studied. For the model in this study, as demonstrated in Fig. 3.11, increase of fluid viscosity significantly influence shearing and tensile failure around the borehole. In a case where low viscosity fluid (μ = 1 cP) was implemented as drilling fluid, the amount of area failing in was considerably lower than in the cases with high viscosity fluid (μ > 100 cP) and shear displacement dramatically increase for the case of 10000 cP.



(a)

(b)



(c)

(d)

Figure 3.11. Slip and shear failure along discontinuities for different drilling fluid viscosity values (a) 1 cP (b) 100 cP (c) 1000 cP (d) 10000cP

The results presented for amount of shear displacement measured in 5 monitoring point show this trend quantitatively in Fig. 3.12a. Additionally, Fig. 3.12b demonstrates variations of pore pressure versus drilling fluid viscosity for the monitoring points. As can be seen in this figure, when viscosity is low, drilling fluid cannot generate slip and tensile failure, therefore, pore pressure has less chance for dissipation. As a result, in general, fluid pressure is high when viscosity is low. With an increase in viscosity, pore pressure can dissipate easier, due to movement of fractures, and therefore, fluid pressure drops. The results presented here, suggest that fluid viscosity has the potential to change the way a reservoir reacts (and fails) when subjected to fluid injection. Therefore, in practical case, by investigating amount of pore pressure in rock mass, a suitable value for viscosity and mud pressure should be adopted.

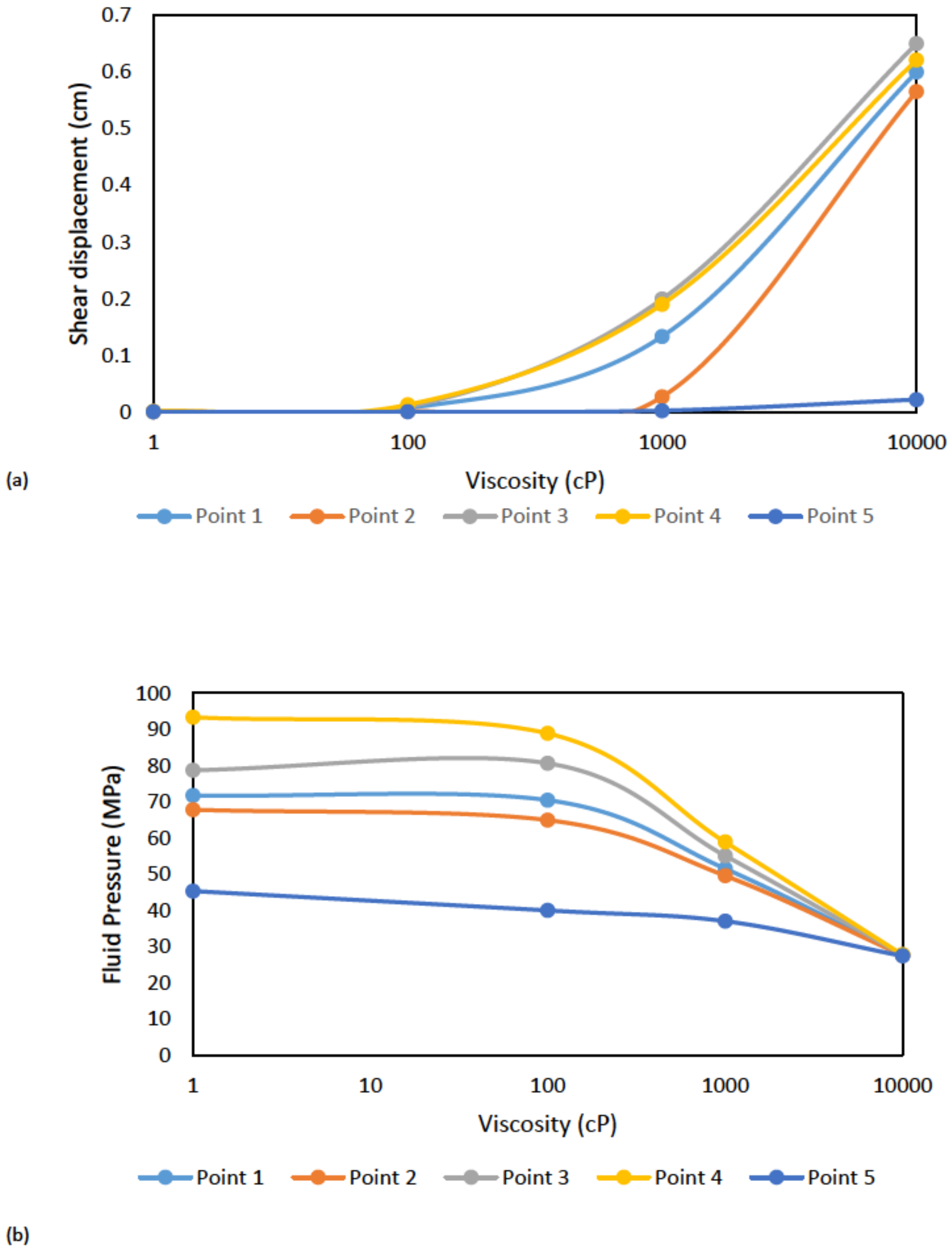


Figure 3.12. Effect of drilling fluid viscosity on simulation results at monitoring points: (a) Shear displacement (b) Fluid pressure

3.7 Conclusions

The insights gained in these three-dimensional DEM simulations presented in this study were aimed at understanding geomechanical influence on borehole stability in naturally fractured rocks, presented here with the case of MB-1 in Northern Perth basin. The results clearly indicate the complexities of drilling in discontinuous rock medium. Simulation results shows that borehole stability largely depends on the rock strength. These simulations were then compared to caliper log. Hydro-mechanical model termed as 'base case' seems to be following the same trend as 'measurement' which is the deformation extracted from caliper log. Simulations show very good match with field measurement with small discrepancies.

Three basic cases termed as HMLP (High mud low pore pressure), HPLM (High pore pressure low mud) and EQMP (equal mud and pore pressure) were simulated after the validation. In HMLP model, large amount of shear displacement was observed and yielded zone around the borehole was significant. For the case of HPLM high pore pressure was applied to the borehole to simulate depletion or production phase. Shear displacement increased when the pore pressure was increased significantly compare to mud pressure. For the model EQMP, a balanced condition was attained with R/r_w value equal 1.0.

As part of parametric study, the effect of mud flow rate, and fluid viscosity on the borehole stability was evaluated. Changes in flow rate showed a clear effect on the amount of tensile failure being triggered as a result of flow rate. Increases in flow rate, greatly increased amount of tensile failure within the model. These results were expected as higher flow rate translate into higher injection pressures and more energy available for rock failure near the borehole. Furthermore, the results suggested shear failure around the borehole increases with an increase in flow rate. This behaviour suggests the very interesting possibility of using flow rate as a parameter to actively control the amount and type of failure to be generated during fracturing.

The amount of tensile and shear failure generated as a result of fluid injection showed a very distinct response to changes in fluid viscosity. In the case where low viscosity fluid ($\mu = 1$ cP) was injected, the amount of area failing was lower than the cases with high viscosity fluid ($\mu > 100$ cP). As a result of this, fluid pressure around the borehole decreases with an increase in viscosity, due to the pore-pressure being dissipated with aid of movement of fractures around the borehole.

3.8 Acknowledgement

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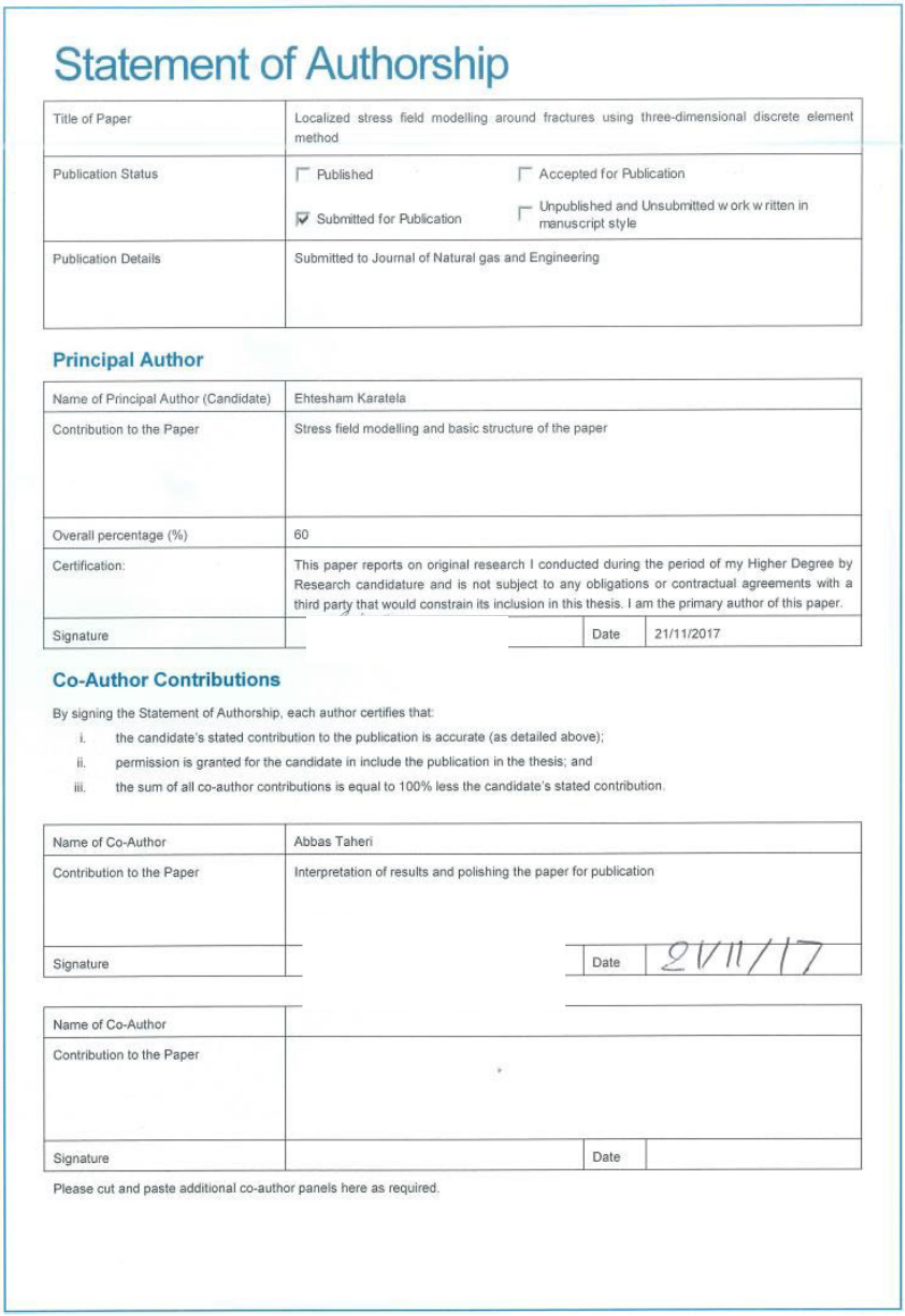
Statement of Authorship



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Signature		Date	21/11/2017

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By signing the Statement of Authorship, each author certifies that:

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ii. permission is granted for the candidate in include the publication in the thesis; and

iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

Name of Co-Author	Abbas Taheri		
Contribution to the Paper	Interpretation of results and polishing the paper for publication		
Signature		Date	21/11/17

Name of Co-Author			
Contribution to the Paper			
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Chapter 4

Paper 3: Localized stress field modelling around fractures using three-dimensional discrete element method

4.1 Abstract

Knowledge of natural stresses is in fractured rock mass is of considerable importance in determining in stability of underground excavations. To analyze stress perturbation in fractured rock mass, a regional model is generated using a DEM based code, 3DEC. Regional model is subjected to several simplifications and three major faults with high dips are modelled. It is then used to estimate stresses on the boundaries of smaller descriptive model termed as base model. Stresses were observed to variate in magnitude at the intersection of discontinuity sets and stress drop was observed at the discontinuity. Also, stress tensors in the model were observed to rotate parallel to the discontinuity. A vertical borehole in base model revealed that high stresses concentrated along discontinuities resulting in high deformation shown in the form of yield zone. Furthermore, base mode was subjected to strength and stress anisotropy analysis. In both cases, due to the effect of discontinuities the induced stress field is non-linear and fluctuating It was observed as part of strength anisotropy that cohesion and friction angle affect stress magnitude but the perturbation is non-linear. Effect of stress anisotropy on stress perturbation found to be more significant for the maximum principal stress as compare with the minimum principal stress.

4.2 Introduction

Borehole stability is a major issue faced in petroleum and mining industry as well as in mining industry as it can result in significant expenditures thus having a significant impact on reservoir production and mine exploration activities. Stability of boreholes have been in unconsolidated formations (Hashemi et al., 2014), heavily naturally fractured rock mass (Karatela et al., 2016) and deep-seated formations (McLean and Addis, 1990).

Subsurface is in a predefined stressed state before a well is drilled. General stress state of the worlds tectonic regions has been studied by World stress map project (Tingay et al., 2005). The project has compiled stress magnitude and orientation from earthquake focal mechanism, boreholes and other sources. These stresses are predominantly generated because of continental and oceanic plate movements. In addition to that various local mechanisms affect the magnitude and orientation of stress at local level which may be contrary to the regional stress. The process of drilling causes the stresses to redistribute themselves and align around the borehole. The altered stress state is responsible for the formation of borehole breakout which is basically shear failure zones along the borehole wall in the direction of maximum horizontal stress (σ_H) and can be reoriented because of discontinuities. Therefore, it is important to investigate the interaction of stresses and rock properties to understand the stability of wellbores. The problem becomes more complicated when we are dealing with fractured rock mass. When stresses redistribute themselves around a borehole in fractured rocks, they not only concentrate around the borehole but their magnitude and orientations are also affected by fractures locally (Brady et al., 1986; Su and Stephansson, 1999; Camac and Hunt, 2004). Therefore, local stress perturbation because of the presence of weak planes will affect the deformation in nearby blocks, thus affecting overall wellbore stability. Traditionally, borehole stability analyses for fractured rocks have been carried out using elasticity or poro-elasticity theory which considers rock as continuum medium (Zhang and Roegiers, 2002; Helstrup et al., 2004). However, such solutions may not be sufficient for rocks with pre-existing fractures. On the other hand, DEM has also been used to investigate the mechanical behaviour of rock mass around borehole. As mentioned earlier, stress perturbation is highly related to the deformation.

When a fractured rock mass is considered, particularly for borehole stability analysis, the fact that all fractures are not under same stress conditions should be properly considered. The orientation and properties of fractures play an important role in describing the local stress state along fractures (Zhang 2013, Bidgoli and Jing, 2014). When fractures have finite size and interact with each other and an intersecting borehole, analytical solution may not be the best way to model such phenomena. In such a situation stress state can be analysed using numerical analysis such as discrete element model (DEM). Distinct Element Model (DEM) has been used to model stress field around underground structures with reasonable success (Brady et al., 1986; Su and Stephansson, 1999; Hakami et al., 2002; Hart, 2003). Brady et al., (1986) simulated stress concentrations introduced by tectonic activity where fractures terminated on other intersecting fractures. These stresses are termed “locked in” since they persist after loading is stopped. The DEM models were able to show this phenomenon (e.g. Homand et al., 1997 and Hakami et al., 2002). Their studies lead to better understanding of principal stress orientation in the area, which are in good agreement with the existing geological information.

A recent study by Hakami et al. (2006), used 3DEC to predict a plausible in situ stress distribution for two candidate sites for radioactive waste disposal. These applications demonstrate that DEM models can be successfully applied to investigate in situ stress fields under complex conditions. Previous studies of stress analysis have been focused on regional stress distribution but investigations regarding stresses around local sets of discontinuities has rarely been reported. Therefore, in this study a detailed analysis on local stress perturbations, stress drop across a discontinuity and effect of stress anisotropy on the stress field was carried out.

In this study firstly, stress field modelling of a part of Northern Perth (NP) basin is carried out using three dimensional DEM code 3DEC to estimate regional stresses in the area. This regional model is used to estimate the stresses around a smaller model termed as ‘model B’. Secondly, stress field perturbations near discontinuities is analysed in model B with and without borehole to observe stress concentrations at fracture intersections. Furthermore, effect of stress anisotropy and anisotropy in properties of discontinuities on stress perturbation were investigated.

4.3 Geological setting and regional stress field of Northern Perth basin

4.3.1 Structural evolution of basin

The Perth Basin is an elongate, Phanerozoic sedimentary basin located in southwest of Western Australia. It extends over 1,000 km of the coastline of southwest Australia and covers both onshore and offshore. Darling fault marks the eastern boundary of the basin and extends westerly to the Perth Abyssal Plain (Mory and Iasky, 1994). It is bounded to the north by Carnarvon basin and to the south by Bremer basin (King et al., 2008). The basin contains a thick sedimentary section with thickness exceeding 15 km ranging in age from Ordovician to Pleistocene (Mory and Iasky, 1994; Reynolds and Hillis, 2000; Rasouli and Southerland, 2014). Two major events of rifting and subsequent infill have been identified in this basin (Mory and Iasky, 1994; King et al., 2008; Rasouli and

Southerland, 2014). A number of shallow marine and fluvial rock formations were deposited during events of tectonic plate extension. Carynginia formation which is a marine rock formation and a proved prospect of shale gas was deposited during the first episode of rifting.

Mory and Iasky (1994) identified three trends of faulting in the Perth basin. An east striking fault system with north south extensions which relates to first episode of rift. Second fault set trends towards north while third north-west striking set of normal faults relate to the final episode of rifting and breaking up of Gondwana (Mory and Iasky 1994; King et al., 2008). Most of these faults have moderate to high dips (King et al., 2008). Fig. 4.1 shows the structural map of Perth basin with varying orientation of stress tensors explaining the complex structural evolution of the basin.

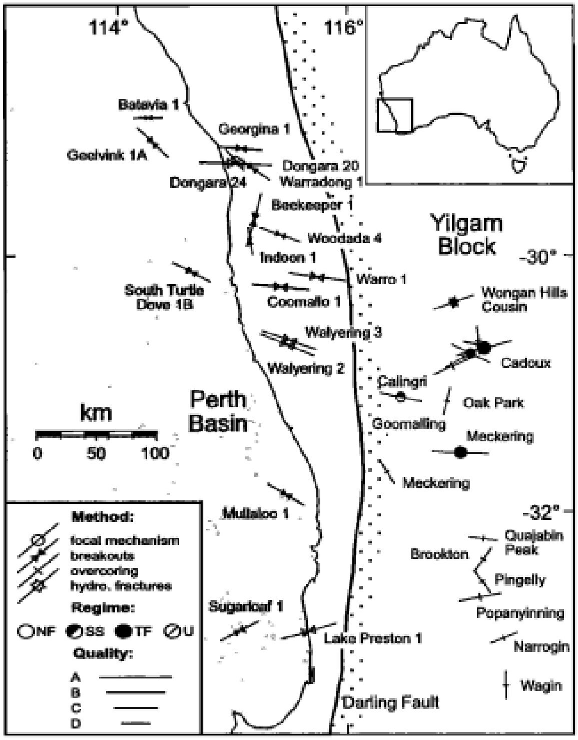


Fig.4.1. Structural elements of Perth basin (after Reynolds and Hillis, 2000)

4.3.2 Stress in the basin

To study the local forces and stresses around a specific well which could be key causes for wellbore instabilities, more detailed analysis should be carried out at the wellbore scale. This can be performed by using an extraction of regional model and applying boundary forces from the regional model like it has been done later in this study. In this section, stress information is used to generate a regional stress model in 3DEC.

Two of the primary stress indicators used for conventional stress analysis are borehole breakouts and Drilling induced tensile fractures (DITF) extracted from image logs. Borehole breakout are stress induced elongations which occur when the maximum circumferential stress exceeds the rock strength which results in spalling of the borehole wall. The orientation of the maximum horizontal stress (σ_H) is perpendicular to breakouts (Bell and Gough, 1979). In some cases, borehole breakout is identified as a set of conjugate shear fractures. DITFs are related to tensile failure of the borehole wall during drilling process and form where the circumferential stress is less than the tensile strength of the rock (Reynolds et al., 2006; Hashemi et al., 2014)

King et al. (2008) and Rasouli and Sutherland (2014) studied tectonic stresses around the northern Perth basin and rock mechanical properties rock formations in the basin using cores from drilled wells. King et al. (2008) analyzed eight wells for borehole breakouts and DITFs. The data interpreted from each well was ranked using World stress map quality ranking system. This ranking system categorizes each well according to the number of breakouts/DITFs, the total length of borehole breakout/DITFs and standard deviation of borehole breakout/DITF orientation giving a rank from A to E, where A represents best quality data and E represents the lowest quality. The A – C quality data is generally considered reliable record of σ_H orientation. However, D and E quality data are not considered to be reliable (Zoback, 2007). In this study, only wells with A-C quality data was used to determine mean σ_H orientation in each well. The mean σ_H orientation was analyses to be 84° N. Bailey et al. (2012) measured the minimum horizontal stress (σ_h) orientation as N81°E from breakouts and N76°E from DITF. Their mean orientation after 16.8° standard deviation is N76°E. This result is in close proximity with the results provided by King et al. (2008).

Vertical stress is calculated by multiplying density of the rock extracted from density log, acceleration due to gravity and height of the column. It generally increases with depth as it is equivalent to the total overburden of the rock at a particular depth. King et al. (2008) found that there is small variation in the vertical stress profiles between the eight wells, but it is not systematic. At 1 km σ_v varies between 21.1 MPa in wells Kingia-1, Mountain Bridge-1 and 22.8 MPa in wells Apium-1. At 3 km σ_v varies between 69.1 MPa in well Redback-1 and 69.6 MPa in well Beharra Springs South-1 (King et al., 2008).

Leak off tests are primarily used to determine the magnitude of Minimum horizontal stress (σ_h). These tests are performed during drilling operations. The test involves increasing the borehole pressure in a specified section until a fracture is formed on the borehole wall. The initiation of fracture is determined by change in pressure versus time slope (Zoback, 2007). This pressure provides an estimate of σ_h magnitude. For this study, σ_h can also be estimated using a relation provided by Rasouli and Sutherland (2014). σ_h in Northern Perth basin was measured to be 7.4 MPa at 0.4 km and 21.0 MPa at 0.82 km (King et al., 2008).

King et al. (2008) and Rasouli and Sutherland (2014) calculated the magnitude of Maximum horizontal stress (σ_H) using a mathematical relation that can only be applied for a vertical well. It was observed that a normal stress regime is dominant in the study area with the order of magnitude as $\sigma_v > \sigma_H > \sigma_h$. The stress anisotropy between minimum horizontal stress (σ_H) and maximum horizontal stress (σ_h) appears to be very low because the magnitude of σ_H and σ_h are very close to each other.

4.4 Modeling methodology

4.4.1 Geometry of the 3DEC model

The model size of a numerical model in general is selected to match the size of the problem domain. In general, in-situ stress field is applied to boundaries of a numerical model to investigate effect of excavation, loading conditions and other model properties. In this study, we aim to analyze stress variation in the investigated region that could be a result of mechanical response to regional loading of fractured rocks. This specifies that technically the problem region has an infinite size. Therefore, it is necessary to make some limitations in model size.

A regional model was built with axial length of 200 meters with three main faults extending across the model (Fig. 4.2). This regional model is termed as 'Model A'. Inside the Model A, a smaller model with two fracture sets was generated at a depth corresponding to the thickness of Carynginia formation. The dimensions of smaller model are 20 X 10 meter and is termed as 'Model B'. This model was generated to observe and analyze the localized stress perturbations generated because of discontinuities. A vertical borehole was simulated at the center of the Model B. It is assumed that discontinuities intersecting the borehole will have influence the stress perturbation. As there are two sets of discontinuities simulated in the model B, it is understood that induced stresses will be affected by both sets of fracture. Therefore, to explain stress perturbation in fractured medium in a simple way, only a single discontinuity in the center is simulated. Model B was simulated with two sets of fracture. Since model B is small in size, therefore, the in-situ stress values being calculated in model A in the model B location is applied to model B boundaries.

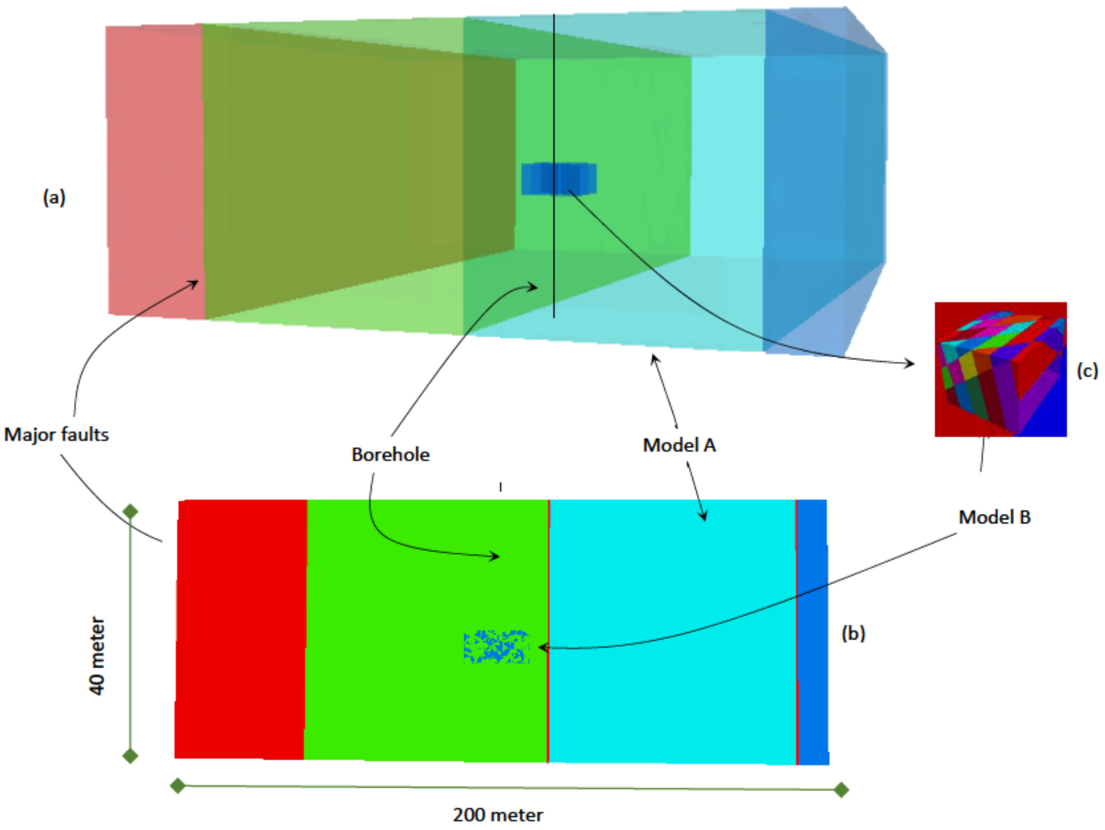


Figure 4.2. 3DEC model geometry (a) Regional model (model A) with three major faults and model ‘B’ (b) Vertical cross-section of regional model with three major vertical faults (c) model B with two fracture sets.

4.4.2 Fracture zone geometry

Based on the analysis presented by King et al. (2008) and Sutherland and Rasouli (2014) two fracture sets were included in model B. Two sets of fractures that are presented in the basin are reproduced in the model as fracture set 1 (F1) runs south-west while fracture set 2 (F2) is present in north northwest direction and can be observed in Fig. 4.2and in schematic representation of model 'B' (Fig. 4.3).

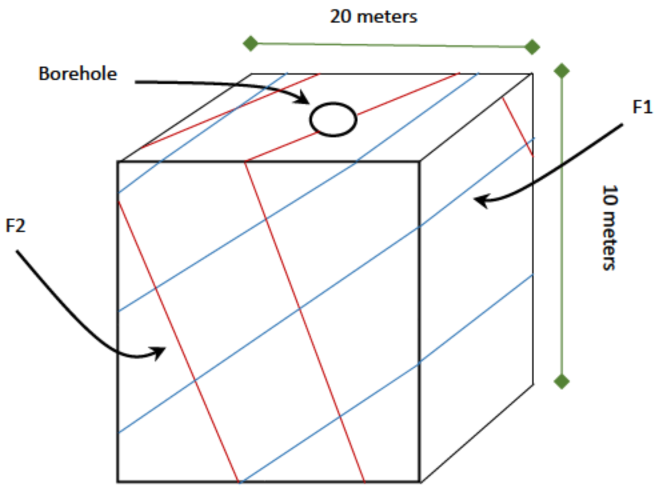


Figure 4.3 Schematic representation of Model 'B' with two fracture sets intersecting the borehole

4.4.3 Initiated stresses and boundary conditions

Vertical stress (σ_v) also known as overburden stress is one of the principal stresses. It is the lithostatic weight or the total weight overlying stratigraphic column. It can be estimated from density log and vertical height of the rock column. As it is a deep-seated environment and the thickness of regional model is significant, σ_v is incorporated as a gradient 21.5 MPa/km which is consistent with the vertical stress gradient of Mountain Bridge-1.

Similarly, magnitudes of major and minor horizontal stresses (σ_H and σ_h) were estimated by Rasouli and Southerland (2014). These magnitudes were used to calculate the ratio of σ_H and σ_h in relation to σ_v which were estimated as 0.818 and 0.788 for σ_H and σ_h respectively. These ratios were then used to apply as stress gradients in the regional model aligned with x-axis and y-axis for σ_H and σ_h respectively.

Rasouli and Sutherland (2014) found that there was no abnormal pore pressure zone in the area. Therefore, a normal pore pressure (P_p) gradient was applied in the analysis. Similar, magnitude of Pp is used in this study which is assumed to be 10.1 MPa/km.

The bottom boundary of the model is fixed as null displacement while σ_H, σ_h and σ_v are incorporated as gradients along the sides and top of the model (see Fig. 4.4). It is important to note that the gradient of each principal stress is initiated in the regional model to make sure the model resembles a realistic stress regime. However, the model B which is more descriptive in structural elements than the regional model absolute values of principal stresses are applied because the size of the model is small. Boundary forces for model B are extracted using LIST command available within 3DEC by giving lower (l) and upper (u) coordinates along x, y and z axis as shown in Fig. 4.4. These boundary forces were then applied to the model.

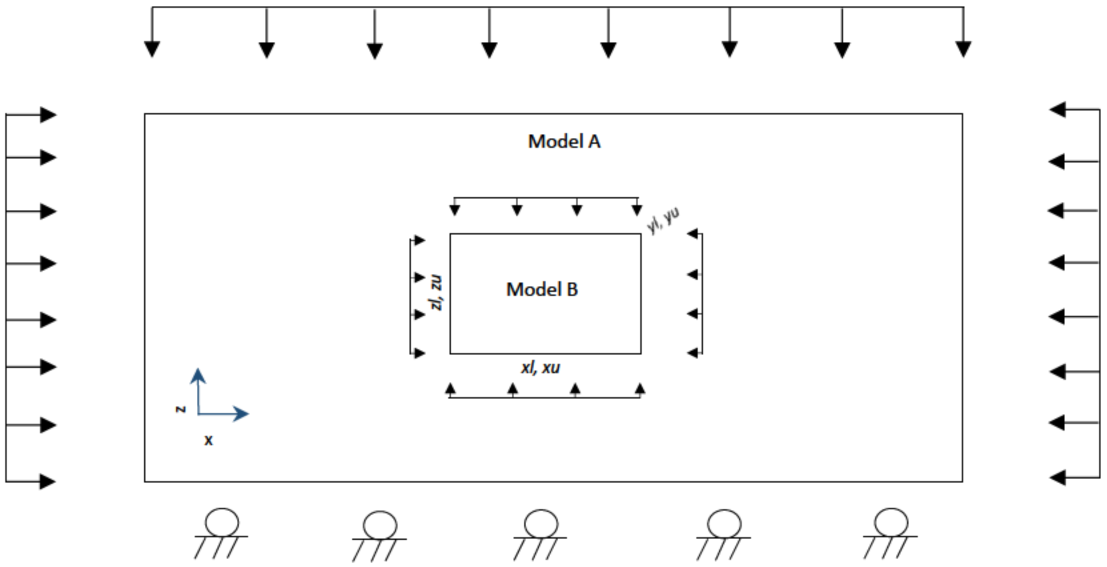


Figure 4.4. Boundary conditions of the Regional model (Model A) and the local model (Model B)

4.4.4 Rock mass and discontinuities properties

The rock mass properties used in the models were adopted from Rasouli and Sutherland (2014). The material model used for rock mass blocks was chosen to be elastic for the determination of perturbed stress field and to determine the plastic zone around the borehole Mohr-Coulomb failure criterion was used in the numerical models. Furthermore, Rock blocks in between fractures are and subdivided with a mesh of triangular finite difference elements. Material parameters used in each model are tabulated in table 4.1.

Table 4.1. Carynginia formation rock properties and fracture properties

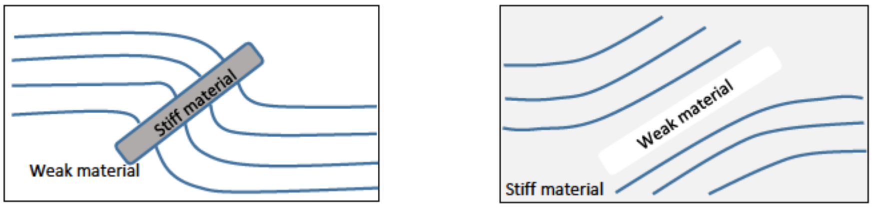
Carynginia formation (Sandy Shale)	Density (kg/m^3)	2600
	Bulk modulus (GPa)	20.90
	Shear modulus (GPa)	10.78
	Friction angle (degree)	28
	Cohesion (MPa)	0.55
	Dilation angle (degree)	0
	Tensile strength (MPa)	8.0
Fracture properties	Normal stiffness (GPa)	9
	Shear stiffness (GPa)	6
	Cohesion (MPa)	0
	Friction angle (degree)	32
	Residual aperture (mm)	0.125
	Zero normal stress aperture (mm)	0.25

Discontinuities between the blocks act as boundaries. The amount of normal and shear displacement between two blocks can generally be determined from the translation and rotation of centroid of each block. Therefore, normal and shear force increments are related to incremental relative displacements (Karatela and Taheri, 2017). In this study, Discontinuity deformation is described using Coulomb slip model where elastic deformation is permitted below a frictional limit. Once the fracture reaches its frictional limit, as defined by strength envelope, shear displacement occurs along the discontinuity. The geological setting of Perth basin suggest that the deformation and strength properties of discontinuities should differ from the surrounding rock mass. It has been established by King et al. (2008) and Rasouli and Sutherland (2014) that Northern Perth basin has experienced several episodes of reactivation.

The fracture parameters utilized in this numerical model are tabulated in table 4.1. In the models, the stiffness of the fracture was applied same to the entire length of discontinuity which may be argued to be unrealistic. In nature, it is more probable that the fracture zone stiffness and strength would vary in different sections of a discontinuity. Simulating such variation in fracture zone properties would of course make the model more complex and while the information about actual geometry and composition of the fracture zones were very limited, therefore it was chosen to simplify the fracture behaviour and consider similar values for all the fractures.

4.5 Stress analysis in the regional model

The pattern of present day stress pattern in a sedimentary basin provide vital information on the sources of stress. Such regional models help us to understand the overall trend of the area and provide basic understanding of geologic features that have influence on the stress pattern. The analysis of present day stress field in numerous regions worldwide has demonstrated that stress rotation occurs near faults and fractures due to either fault slip on active fault or variable rock mechanical parameters. Barton and Zoback (1994) explained rotation of breakouts due to slip on an active fault intersected by boreholes. Barton and Moos (2010) also suggested that rotation of breakout occur due to plane of weakness such as a fracture intersected by or present near a borehole. A prominent rotation of σ_H stress tensors is associated with stress perturbation in a medium with contrasting stiffness. This phenomenon is schematically represented in Figs 4.5a and 4.5b.



(a) (b)

Figure 4.5. Orientation of σ_H stress tensors across a discontinuity (a) σ_H pattern reorienting perpendicular across stiff material. (b) σ_H pattern reorienting parallel to weak material (Modified from Rajabi et al., 2016)

In addition to the rotation of σ_H in-situ stress tensors a phenomenon termed as 'locked in stresses' is also observed when the stressed fault or a fracture is subjected to slip. If resulting shear stresses are plotted, prominent zones of extension and compression are developed at the tip of discontinuity. This spatial heterogeneity in initial stress state can develop in a discontinuous medium. Fig. 4.6a shows a schematic representation of these zones in a discontinuous medium. The mechanism of these stress concentrations is explained by Kattenhorn et al. (2006). When slip occurs across a discontinuity few strands of secondary faults are formed at the fault tips which are responsible for these localized stress concentrations. A vertical cross-section of magnitude along the fault tip will have marked deflection (Fig. 4.6b).

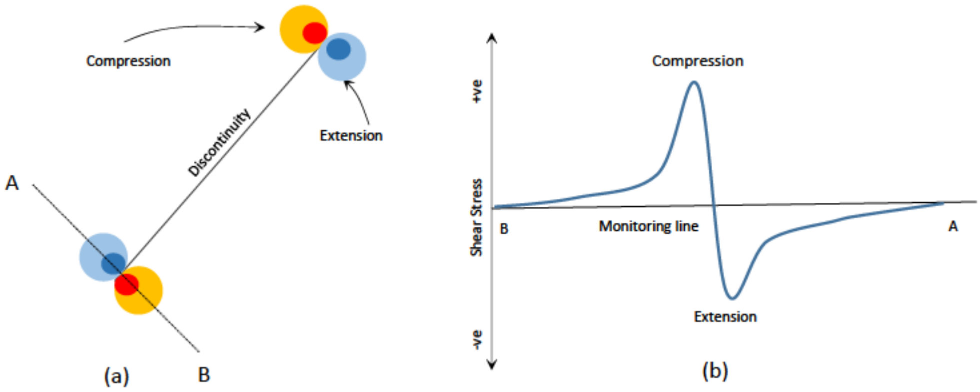


Figure 4.6. Shear stress at the tip of a discontinuity. (a) Schematic representation of shear stress magnitude perturbation. (b) Profile of stress magnitude deflection across line A-B

A specific stress path followed during geologic history (several episodes of rifting and compression in case of NP basin) and physical processes such as slip and fracturing occurring in stages of history. This result from spatial heterogeneity of stress state can be an important factor in borehole stability analysis and production of fluids from the subsurface. In this section, regional variability in orientation of in-situ stress values in the basin is discussed. For this purpose, a regional model including three main fault plans is generated to investigate effect of faults on stress regime in the area and to estimate traction on the boundaries of model B Fig. 4.7.

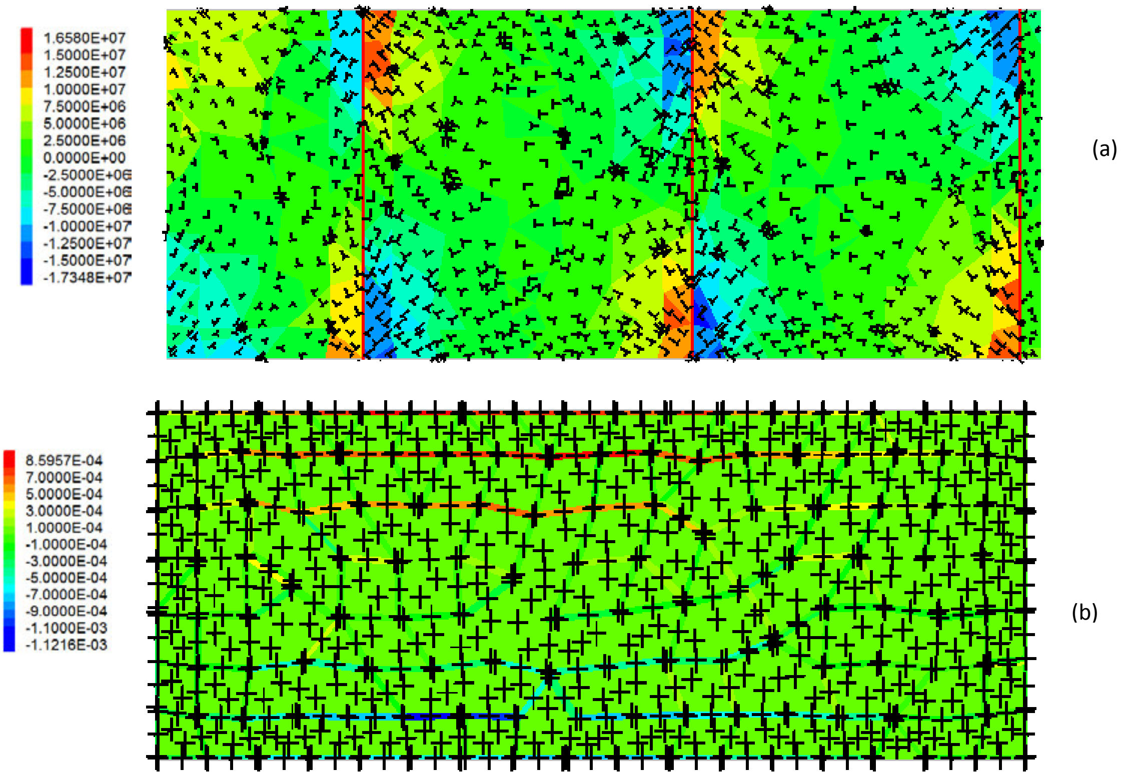


Figure 4.7. (a) Vertical cross-section of Model A showing no regional faults and maximum principal stress tensors. (b) Vertical cross-section of Model A showing regional faults and rotation of stress tensors from perpendicular to near parallel near the fault.

Fig. 4.7 shows two phenomena of discontinuous medium. Firstly, shear stress contours were observed to concentrate near the tips of discontinuities in a set of extension and compression zone. The perturbed stress field is presented in the vertical cross section of regional model (Fig. 4.7a). Secondly, Stress tensors for maximum principal stress are shown in Fig. 4.7. Furthermore, fig. 4.7b represents regional model with no faults to provide a basic comparison between models with discontinuity and without discontinuity.

Our results show perturbation of shear stresses near fault tips laterally across the simulated model because of the presence of discontinuities as presented in Fig. 4.7a. In Fig. 4.7b no variation is observed primarily because of lack of discontinuities. For the purpose of simplification, the model was simulated with a single material. Therefore, stress perturbation because of lithological variation cannot be observed in these models.

σ_H tensor orientation is observed to have been controlled by geologic structures. As presented in Fig 4.7a, stress tensors tend to reorient themselves near the discontinuity.

Furthermore, this deflection is more significant at fault tips where stress magnitude is concentrated. On the contrary, no reorientation of stress tensors is observed in Fig. 4.7b because of lack of discontinuities.

Our investigation in the NP basin revealed that localized perturbation of stresses particularly due to the presence of geologic structures such as fault and fractures. Faults, fractures and also lithological contrasts have been emphasized as being important control on third-order σ_H orientation in numerous sedimentary basins around the world. Image log analysis by Rajabi et al. (2015) showed that large, local rotation of borehole breakouts which determine the orientation of σ_H, occur near faults and fractures. These authors emphasized that abrupt changes of σ_H were more consistent with the presence of faults while gradual rotation occur close to lithological changes. Our numerical representation of NP basin clearly shows the rotation of stress tensors near the major faults and is in accordance with the observations provided by Rajabi et al. (2015).

4.6 Stress analysis in the localized model

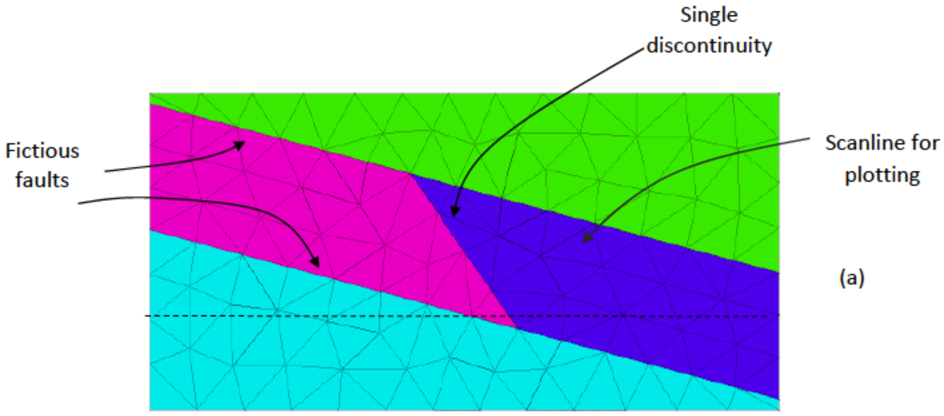
In this section, we aim to characterize stress perturbation induced by the presence of pre-existing discontinuities. To do so base model is used to simulate stress perturbations as a base case. However, in such a model a number of complexities can affect the induced stresses. Therefore, in order to exclude local intricacies for areas such as base model where a number of discontinuities can aid in stress perturbation of the stress field, we have chosen to initially restrict our study to a simple case with one fracture where constraints are clearly defined.

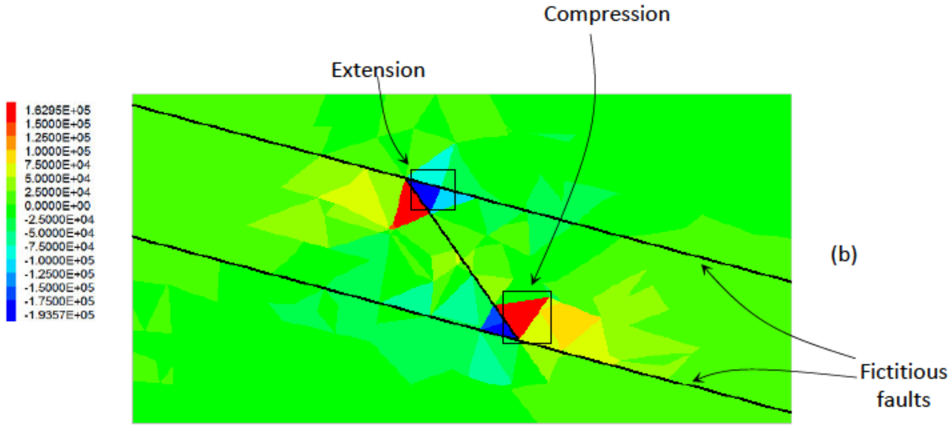
4.6.1Single fracture analysis

Numerous studies around the world have demonstrated that the orientation pattern of maximum horizontal stress (σ_H) at small scale can either be simple, suggesting that the present-day stress can be linked to far field stress or it can be very complex due to interaction of different subsurface structures and forces at different scales. We, therefore, in the first stage, consider a single discontinuity cutting into a homogenous medium.

As described above a spatial heterogeneity in an initial stress state can develop in a jointed and fractured medium prior to excavation. This results from the stress path followed during the geologic history of the medium and physical processes related to fracturing and slip separation along discontinuities that may have occurred at different stages of geologic history. Spatial heterogeneity of the stress state can be a vital parameter in the design of underground excavations such as borehole, particularly if the resulting perturbation is affecting stability.

Stress perturbation because of discontinuity is represented by generating a single fracture model as presented in Fig. 4.8a. Two discontinuities extending to the model boundary, shown an “Fictitious faults” in Fig. 4.8a, are joined using ‘join’ command in 3DEC so it does not play any role in the on the stress field. The discontinuity will result an isotropic homogenous medium and we will be able to analyses stress perturbation induced by the discontinuity in the centre. The central discontinuity has high stiffness to observe significant rotation of principal stress tensors. The presence of this discontinuity develops compressive and extensive zones of shear stress at the tips (Fig. 4.8b). These perturbed stresses are termed as “locked in” stresses. Furthermore, maximum principal stress tensors are plotted in Fig. 4.8c.





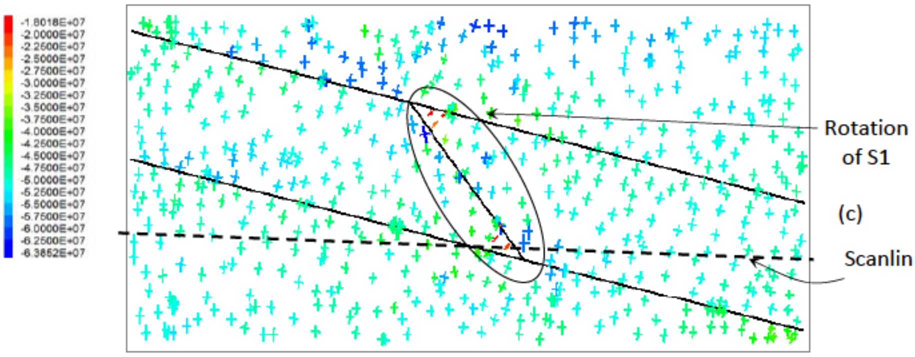
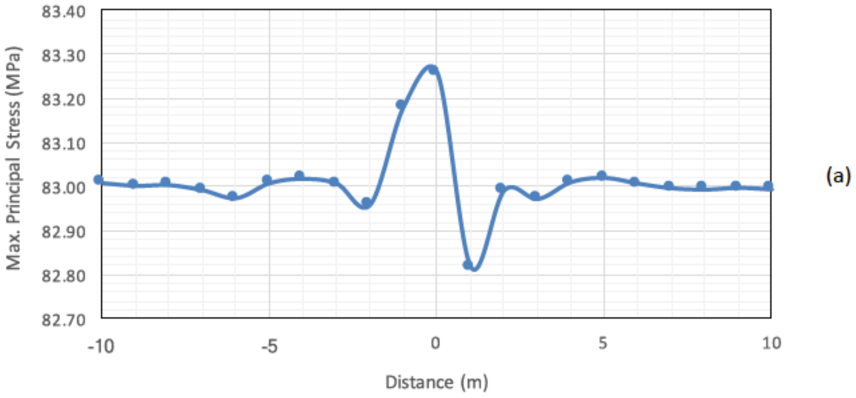


Figure 4.8 Stress analysis in presence of a discontinuity bounded by fictitious faults (a) Geometry of the model (b) shear stresses concentration at discontinuity tips (c) Principal stress tensor rotation and concentration at discontinuity tips.

For each model, stress perturbation showed particular properties illustrated in Fig. 4.8. Fig. 4.8 shows that: a) The stress perturbations are observed only when slip occurs on the discontinuity, b) The stress distribution is symmetrical with extensive and compressive zones relative to the centre of the discontinuity, c) The stress perturbations are observed in the vicinity of discontinuity with maximum magnitude concentrated at the tips (Fig. 4.8b), d) Rotation of stress tensors occurs as a result of the discontinuity, particularly at the tips of the discontinuity. The colour of stress tensors in Fig. 4.8c relates to the magnitude of maximum principal stress and it can be observed that two relative zones of compression and extension are formed.

Furthermore, maximum and minimum principal stresses are extracted from the base model along the scan line is presented in Fig. 4.9. A scanline of measurement points was placed along x-axis which is shown in Fig. 4.8c.



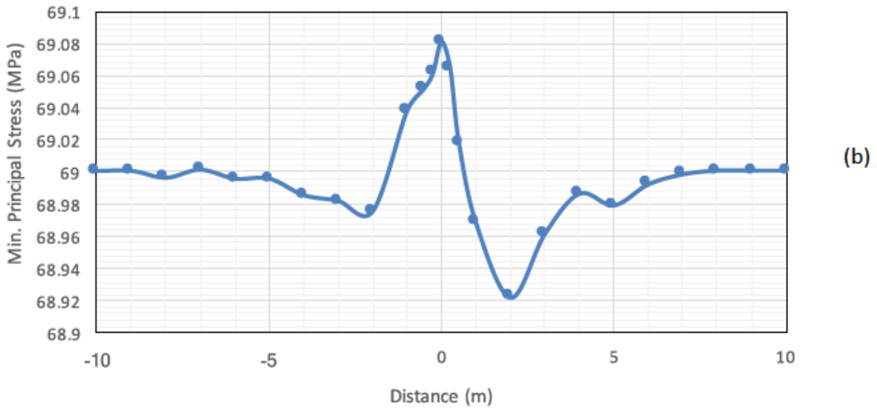
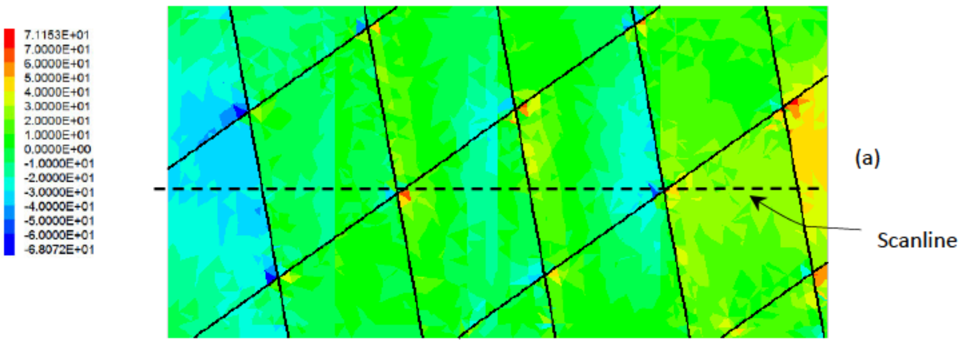


Figure 4.9 Stress perturbation in the localized model with a single discontinuity (a) Maximum principal stress (b) Minimum principal stress

The simulation result, presented in Fig. 4.9, shows that both maximum and minimum principle stress values (i.e. σ_1 & σ_3) fluctuates in the vicinity of the discontinuity and is in good agreement with the results presented in Fig. 4.8c. Background σ_1 in Fig. 4.9a is 83 MPa and at the tip of discontinuity highest magnitude reaches to 83.3 MPa the lowest stress magnitude is reaches to 82.8 MPa. Similarly, σ_3 magnitude in the intact rock is 69 MPa, while the maximum is reached to 69.1 MPa and lowest magnitude is achieved to 68.9 MPa.

4.6.2 Multi fracture analysis

After analyzing stress perturbation around a single discontinuity and establishing constraints on the induced stress field, base model is subjected to stress analyses. Development of shear stresses at the intersection of discontinuities is presented in Fig. 4.10a. Similarly, stress tensor principal stress is shown in Fig. 4.10b.



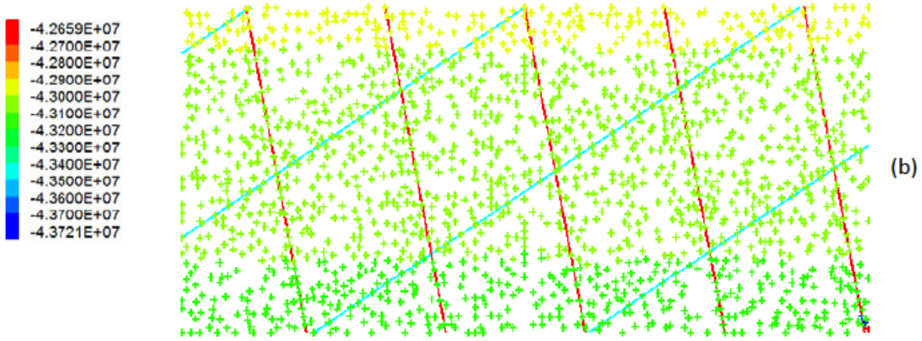


Figure 4.10. Stress distribution in base model (a) Shear stress concentrations at joints intersections (b) Maximum principal stress tensors rotation near discontinuity. (c) No rotation of principal stress tensor in a model with no joint sets.

Similar to the results previously observed for a single joint (see Fig. 4.8), locked in stresses were observed at the intersection of joint sets in Fig. 4.10a. The figure shows that at the intersection of two joints stresses are concentrated as compression and extension stresses. If a borehole is considered to drill in jointed rock mas, this induced stress field can significantly affect the stability of borehole wall and also the flow of hydrocarbon.

Similarly, stress tensors for the principal stress are presented in Fig. 4.10b which is in good argument with the single fracture model. It can be observed in Fig. 4.10b that stress tensors tend to rotate parallel near discontinuities.

Furthermore, the maximum and minimum principal stresses which are extracted from the model are presented in Fig. 4.11. A scanline of measurement points was placed along x-axis which is shown in Fig. 4.10a.

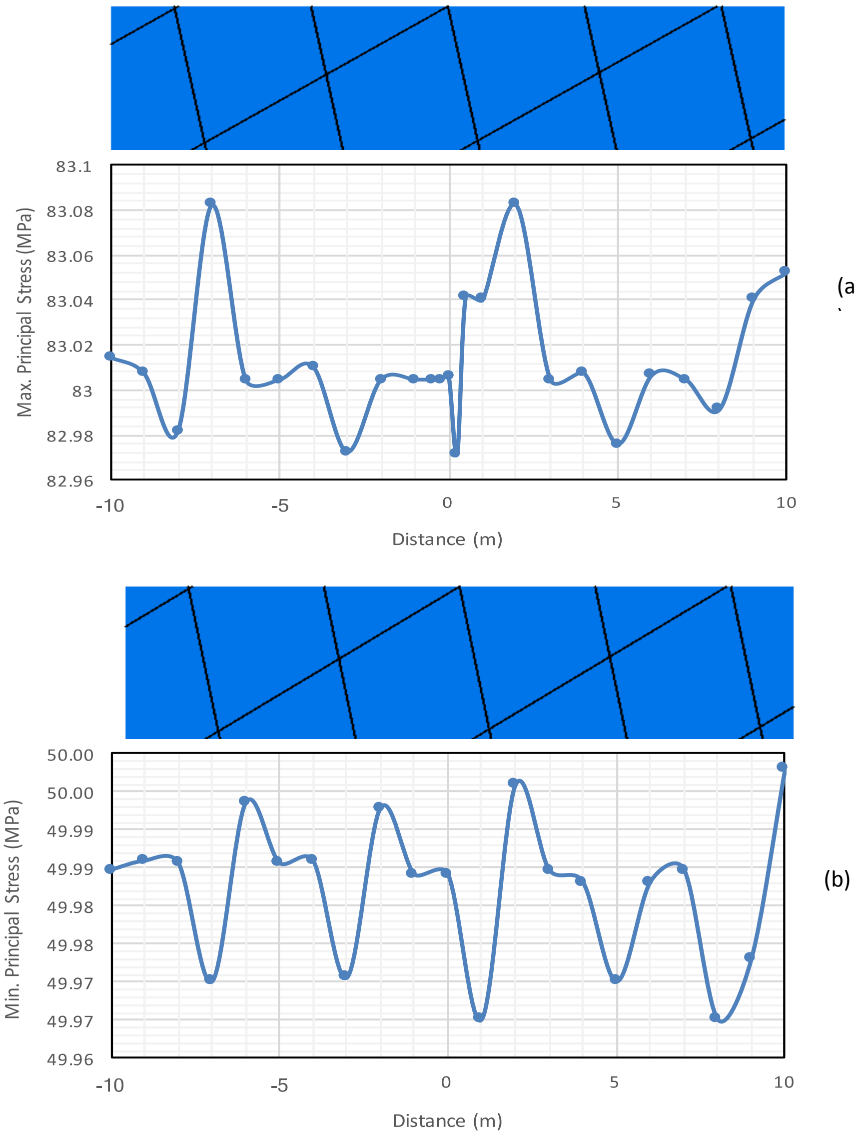


Figure 4.11 (a) Maximum principal stress distribution along the scanline (b) Minimum principal stress distribution along the scan line

From Figs 4.11 a and b two phenomena can be observed. The place in the model where two fracture sets intersects, stress field is perturbed developing zone of compression and extension shown in Figs 4.11a and b by crest and trough. Similarly, at the point where scanline passes through a discontinuity, a mark stress drop is observed because the discontinuity hinders the transmission of stress. Stress drop at the discontinuity is in good agreement with the results presented early stress perturbation studies.

4.7 Effect of borehole on stress concentration

It has been established that stresses concentrate around the excavation because the original state of stress had been disturbed and to attain the equilibrium of forces stresses reorient themselves. These stresses are comparatively easy to evaluate when a rock is isotropic, homogenous and continuous (Al-Ajmi, 2006). Failure in terms of borehole breakout and tensile failure are predictable in such media. However, when dealing with a medium that is discontinuous, stresses in addition to existing plane of discontinuity play a vital role in rock failure (Karatela et al., 2016)

Similarly, stresses around the borehole are in a discontinuous medium are subjected to two different phenomena: (1) Stress magnitude concentration around the borehole compare to far field stress due to borehole excavation and, therefore, in-situ stress disturbance, (2) Stress concentration around the discontinuities. To analyze stresses around a borehole in a discontinuous medium, a borehole in the center of model B is simulated. Results of maximum principal stress contours in a vertical cross section are shown in Fig 4.12a. Furthermore, deformation around borehole caused by concentration of in-situ stress is presented in Fig. 4.12b.

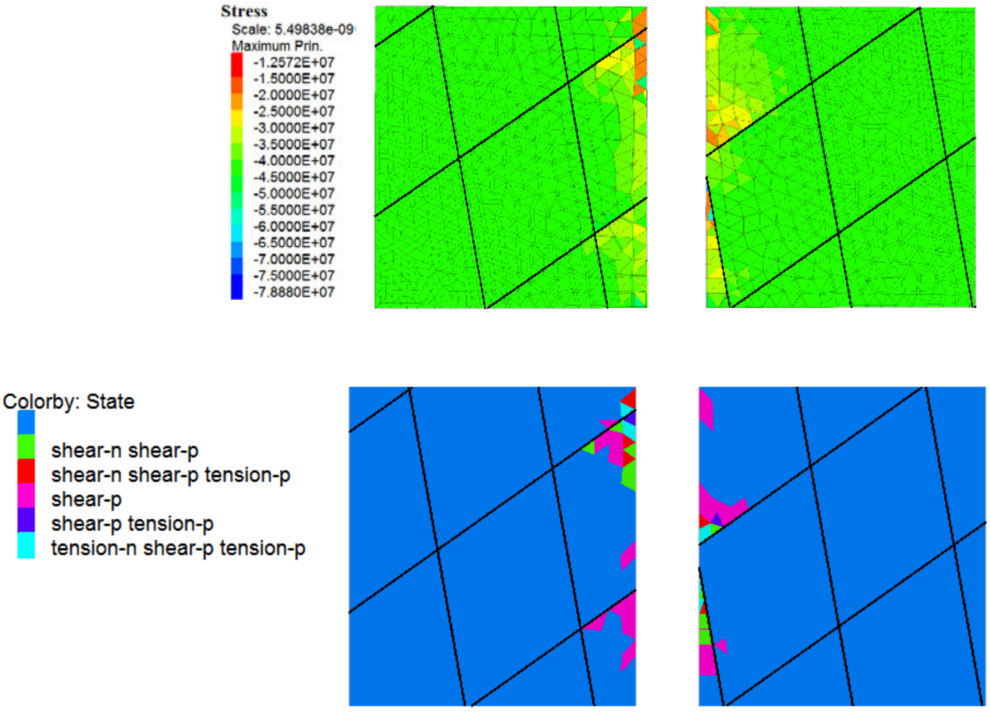


Figure 4.12 Results of a borehole simulation (a) Vertical cross-section of maximum principal stress. (b) Vertical cross-section of yield zone.

Fig. 4.12a clearly shows high stresses at borehole wall and along the discontinuities. Hot colors in the model are related to higher magnitude of maximum horizontal stress. In addition, Fig. 4.12b shows the formation of yield zone because of high stresses. In 3DEC plastic flow of material is indicated by yielding of the blocks. The failure mechanism is indicated by yielding of the blocks. Initial yielding occurs at the start of simulation indicating unbalanced system. As the system stabilizes, some of the elements don't fulfil the yielding criterion. Such elements are termed as "yielded in past" and indicated in Fig. 4.12b by –p. Active yielding elements at the end of simulation are termed as "yielding now" and shown as –n. Elements yielded in the past and yielding now together define the plastic zone around the borehole (Itasca 2013). Furthermore, it can be extrapolated that the deformation zone is not only formed because stress concentration around borehole but also because of the presence of discontinuities in the model. These results are in conjunction the results presented in Karatela et al. (2016).

4.8 Effect of anisotropy

Rock mass is complex in nature because of the presence of discontinuities of various sizes, properties and orientation. Therefore, the mechanical behavior of rock mass is anisotropic and not linear elastic. Anisotropy is defined as variation of properties with respect to the direction along design and analysis of rock structure. A rock mass is generally classified as anisotropic when due to existence of a single discontinuity or joint set or multiple discontinuity and joint set with different properties, it exhibits different behavior in different direction. In other words, in an anisotropic rock mass, properties are directional dependent. Additionally, the rock mass may be subjected to isotropic or anisotropic in-situ stress condition.

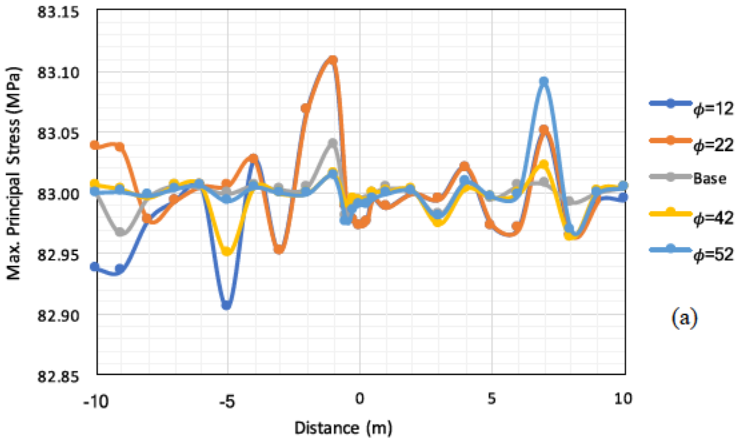
Effect of strength and stress anisotropy on the stress concentration and therefore stability of underground excavations is important to understand. Therefore, the objective of this section is to investigate effect of strength and stress anisotropy on in-situ stress concentration in the base model.

4.8.1 Strength anisotropy

Major and minor discontinuities such as fault zones and small-scale fractures inherited from previous tectonic episodes mainly influence deformations at later stage. Because of the complex orogenic history, continental crust exhibits strength anisotropy caused by tectonic and geological activities. Therefore, stresses in continental crust are affected by the presence of these large scale and small-scale discontinuities in terms of magnitude and tensor orientation. From the literature friction angle and cohesion are considered to be key properties of a discontinuity that affect stress perturbation.

To do so, Mohr-column shear strength parameters of two joint sets (i.e. cohesion and friction angle) were considered to create anisotropic rock mass and to study stress perturbation in fractured rock mass. Base model is used in this section which contains two sets of discontinuities. Therefore, to analyze the strength anisotropy, one of the fracture set was simulated as the base case while the other set had a different friction angle.

Induced stress magnitude for σ_1 and σ_3 are presented in Fig 4.13. As it is shown in Fig. 4.13 has a friction angle of 12° and is increased until 52°. Base case has a friction angle of 32°.



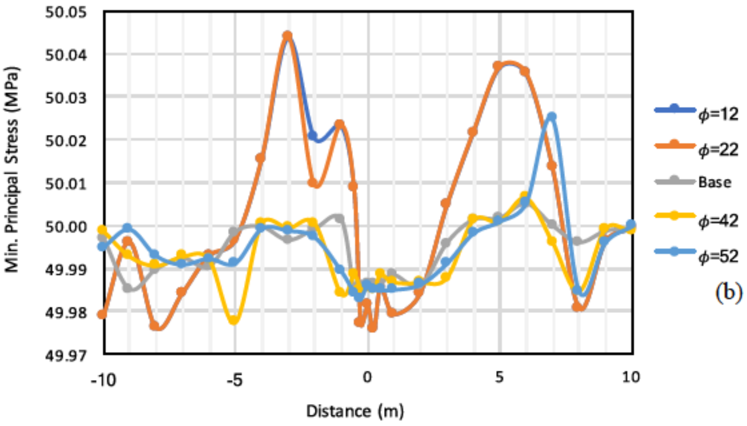
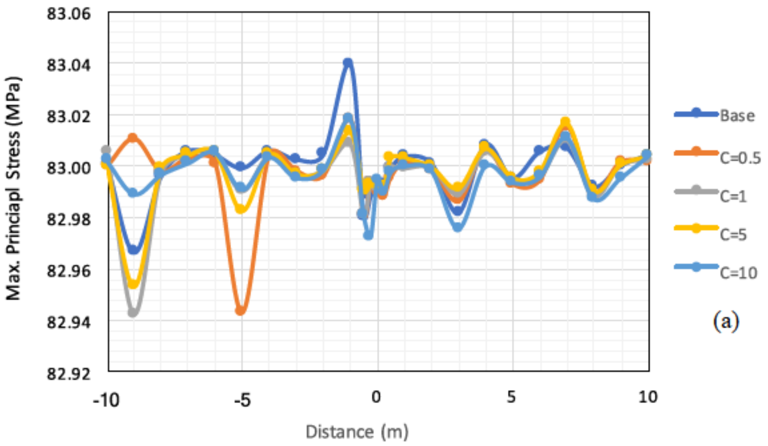


Figure 4.13 Stress perturbation because of strength anisotropy- friction angle (a) Maximum principal stress (σ_1) (b) Maximum principal stress (σ_3)

Fig. 4.13a shows σ_1 perturbation along the scan line. Two observations can be made from this figure. Firstly, perturbation is observed at discontinuity intersections with two marked deflections. Secondly, the variation in magnitude is not significant and is in a range of 0 to 0.10 MPa. Similarly, Fig. 4.13b show perturb magnitude of σ_3 with two marked deflections which determine the formation of relative compression and extension zones. Magnitudes of σ_1 and σ_3 as a function of friction angle (ø) showed that the variation is nonlinear. A rapid decrease in effect is observed as the friction angle is increased (Fig. 4.13a and b)

Another important property of a discontinuity is cohesion. As explained in the previous section base model contains two sets of discontinuities. Therefore, to analyze the strength anisotropy because of cohesion, one of the fracture set was simulated as the base case while the other set had a different cohesion. The base case cohesion is 0, therefore, it is increased until 10 MPa as shown in Fig. 4.14 determined by C0.5 up to C10. Stress perturbation of σ_1 and σ_3 is presented in Fig. 4.14 a and b respectively.



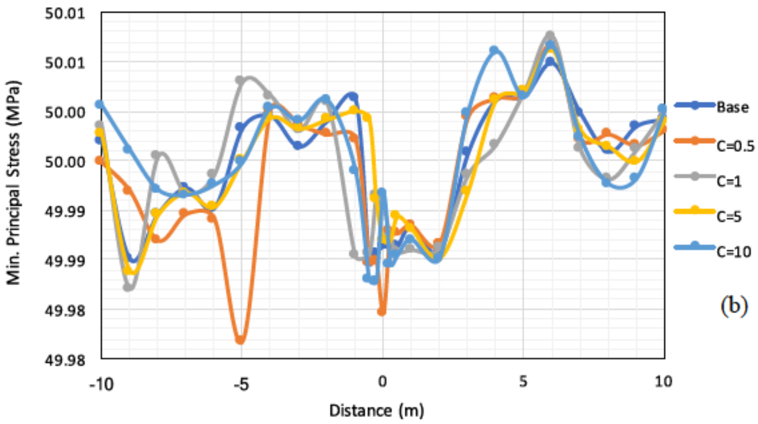


Figure 4.14 Stress perturbation because of strength anisotropy- Cohesion (a) Maximum principal stress (σ_1) (b) Minimum principal stress (σ_3)

In Fig. 4.14a σ_1 stress perturbation because of change in cohesion along the scanline is presented. It is observed that all the models follow the base case trend. However, perturbed magnitude of σ_1 and σ_3 is non-linear. It is further observed that at the intersection of discontinuities a crest and trough of relative compression and extension is formed and is shown in Fig. 4.14. Also, at points where scanline intersect a discontinuity stress drop is observed. Two points at -5 and 10 σ_3 appear to have shown a sharp deflection in magnitude which are the intersection points of discontinuities (Fig. 4.14b)

4.8.2 Stress anisotropy

It has been emphasized that local stresses close to discontinuities are very important in design of well bore stability and excavation process. Current developments in hydraulic fracturing analysis in unconventional reservoirs has revealed that stress anisotropy and presence of discontinuities can significantly influence the direction of induced fractures. It is a well-known fact that stresses in the nature are not isotropic. On the other hand, there is a significant contrast in the magnitude of horizontal principal stresses.

Therefore, to determine the effect of stress anisotropy on the induced stress field K which is ratio of horizontal stress to vertical stress (σ_H/σ_v) was modelled. Stress anisotropy analysis was carried out in two stages, in the first part magnitude of σ_H was considered equivalent to σ_h ($\sigma_H = \sigma_h$). Similarly, in the second stage σ_H magnitude is modelled as twice of σ_h ($\sigma_H=2\sigma_h$). For each stage K values of 0.5, 1 and 2 were modelled. When the value of K is 1 the stresses are considered as isotropic, such a condition is rarely found in nature but for the purpose of analysis it is included in the analysis. Results of analysis are presented as induced magnitudes of σ_1 and σ_3 in Fig. 4.15 for stage 1 and in Fig. 4.16 for stage 2.

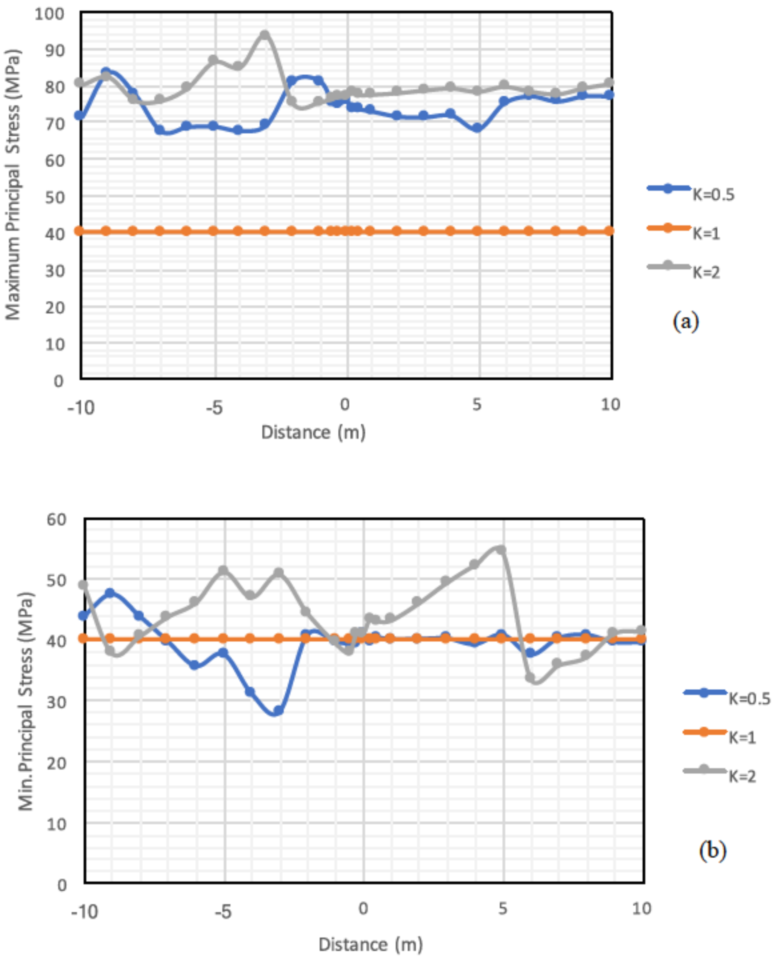


Figure 4.15 Stress perturbation because of stress anisotropy-$\sigma_H = \sigma_h$ (a) Maximum principal stress (σ_1) (b) Minimum principal stress (σ_3)

From the results presented above in Fig. 4.15a and b it can be observed that when stresses are isotropic (K=1), no perturbation is observed primarily because the whole system is in equilibrium. For the isotropic case magnitude of σ_1 and σ_3 is consistent at 40 MPa. However, anisotropic stresses (K=0.5 and K=2) had some minor deflections along the scanline. It can be observed in Figs. 4.15 a and b that graph lines for K=0.5 and K=2 follow a similar trend but the difference in deflection is very high. These phenomena can be explained by the stress regime K models. For instance, K=0.5 implies that vertical stress (σ_v) is the maximum principal stress and represents normal stress regime.

Similarly, K=2 implies that σ_H is twice as σ_v and σ_v is the least principal stress, therefore representing reverse fault regime.

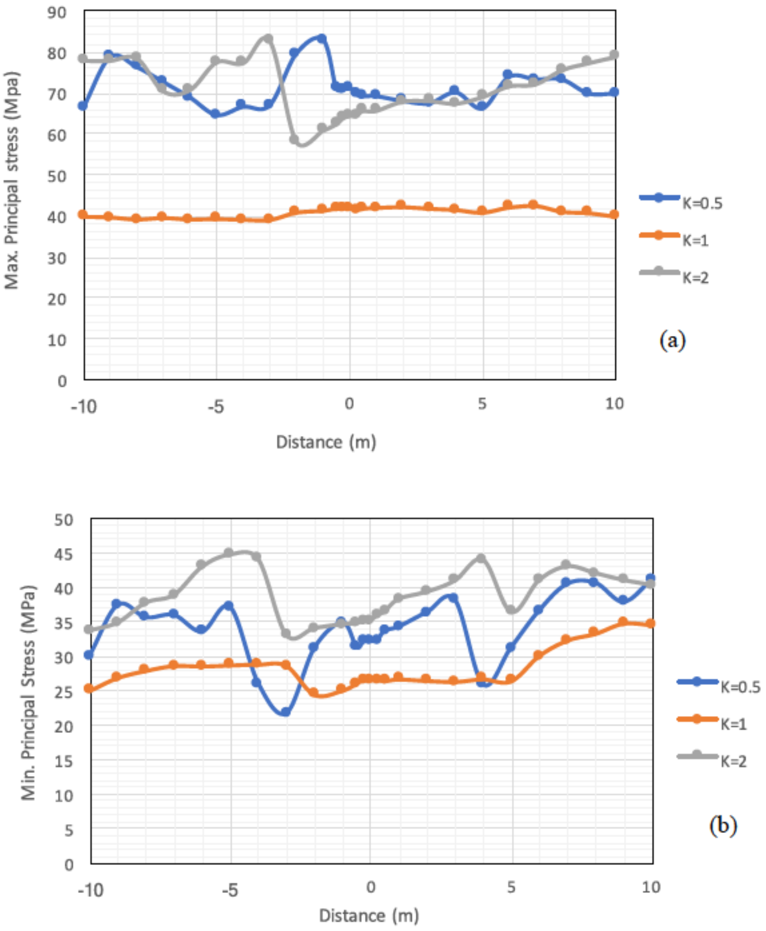


Figure 4.16. Stress perturbation because of stress anisotropy-$\sigma_H = 2\sigma_h$ (a) Maximum principal stress (σ_1) (b) Minimum principal stress (σ_3)

Results for stage 2 ($\sigma_H = 2\sigma_h$) are presented above in Fig. 4.16a and b. It can be observed that when stresses are isotropic (K=1), minor perturbation is observed at two points along the scanline. It is primarily because isotropic stress conditions are most stable. For the isotropic case magnitude of σ_1 is consistent at 40 MPa but for σ_3 two sharp deflections are observed parallel to the anisotropic K ratios. Anisotropic stresses (K=0.5 and K=2) show significant perturbation along the scanline for both σ_1 and σ_3. Similar to the first stage, K=0.5 represents normal stress regime and K= 2 represents reverse fault regime. It can be observed in Figs. 4.16 a and b that graph lines for K=0.5 and K=2 follow a similar trend but the difference in deflection is very high at two specific points. It was confirmed from the model that these two locations had developed zones of relative compression and extension.

Stress anisotropy analysis showed that isotropic stresses were the most stable case and had no or minor perturbation. However, such a case does not exist in actual working conditions. Higher contrast in in-situ stress simulated in the model relates to higher stress perturbation as shown in Figs. 4.15 and 4.16.

Strength anisotropy and stress anisotropy analysis showed that however stress perturbation is affected in both cases, the induced stress field is not linear. Change in discontinuity parameters had a sharp effect on discontinuity intersection and single discontinuity. However, when stress anisotropy is modelled, the deflection is only observed at the intersection of joints and no variation was observed where single discontinuity is crossed by scanline. The predicted stress distribution of shear and deviatoric stress is very helpful to understand the risk of failure. Regions of high stress are related to highly susceptible to failure as determined in the section explaining stresses around borehole. Therefore, this data set can be useful in risking the probability of tectonic activity.

4.9 Conclusion

Stress distribution in a small-scale area has several influencers apart from the tectonic elements. This local stress distribution exists because of small scale geological features which may have a significant influence on large scale. Constraining these localized stress perturbations is a key element in analyzing borehole stability and related underground excavations. In this study, perturbation of the in-situ stresses is investigated in a section of northern Perth basin. First of all, a regional model is generated with three major discontinuities with steep dips. This regional model is used to estimate traction on a local model which has two orthogonal fracture sets. The local model is then subjected to stress perturbation analysis. Furthermore, effect of strength and stress anisotropy on stress perturbation is also investigated. The following conclusions were drawn from this study.

1. Small scale fractures and large-scale faults are one of the most important geologic fracture that affect stress perturbation in a fractured rock mass. It was observed that stresses concentrated at fault tips divided by two zones of compression and extension relative to the center of the discontinuity. Shear stresses at the tip of faults in the regional model are induced up to 16 MPa.
2. Stress perturbations in the base model are presented. σ_1 and σ_3 were extracted along the scanline and a marked deflection at joint set intersection was observed.

Also stress drop at the discontinuity was observed. Perturbation of σ_1 and σ_3 is not large in terms of magnitude and is between 0.2 to 0.8 MPa. In addition to the magnitude of stresses at tips of discontinuity, it was observed that when stress tensor pass through a material of low stiffness in this case, a discontinuity, it tends to rotate parallel to the discontinuity.

3. A vertical borehole in the base model showed that stresses concentrated along discontinuity which relates to the idea of stresses concentrating along discontinuities. This phenomenon is evident from the deformation along fractures showed in term of yield zone.
4. Effect of stress anisotropy on stress perturbation is found to be very significant whereas strength anisotropy which was studied by changing of friction angle and cohesion in one of the discontinuities slightly affected stress perturbation. In both cases, due to the effect of discontinuities the induced stress field is non-linear and fluctuating. This is mainly because stress drops at the discontinuity. Effect of stress anisotropy on stress perturbation found to be more significant for the maximum principal stress as compare with the minimum principal stress.

4.10 Acknowledgements

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Appendix A

In this section data files for the models simulated as part of different investigations are presented.

Paper 1

A data file for a single model is presented.

```
new
config thermal tflow
round 0.0030
edge 0.0060
block -1.5,-1.5 -1.5,1.5 1.5,1.5 1.5,-1.5
arc (0.0,0.0) (0.155,0.0) 360 24
jset 45.0,0.0 4.25,0.0 4.25,0.0 0.065,0.0 -1.5,-1.5 0
jset 315.0,0.0 4.25,0.0 4.25,0.0 0.065,0.0 -1.5,1.5 0
gen edge 1.0
group zone 'User:material'
zone model mohr density 2278.0 bulk 1.88699996E10 shear 7.72E9 friction 36.0 cohesion 6300000.0 tension 2.07 dilation 0.0 range group 'User:material'
joint model area jks 5.9999997E11 jkn 8.9999999E11 nstable 0 jfriction 32.0 jcohesion 0.0 jtension 0.0 jdilation 0.0 zdilation 0.0 jperm 83.3 ares 1.25E-4 azero 2.5E-4 empb 1.0 expa 3.0
set jmatdf=1
prop jmat=1 jks=5.9999997E11 jkn=8.9999999E11 jfriction=32 jcohesion=0 jtension=0 jdilation=0 zdilation=0 jperm=83.3 ares=1.25E-4 azero=2.5E-4 empb=1 expa=3 nstable=0
boundary stress -3.684E7,0.0,-3.684E7
insitu stress -3.684E7,0.0,-3.684E7 szz 4.386E7
step 500
delete range -0.07521368,0.14102565 -0.117521375,0.09871795
delete range -0.13228689,0.08515779 -0.076861,0.13528015
delete range 0.13377348,0.14968406 0.030977417,0.055727214
delete range -0.13759042,0.09311308 -0.14580688,-0.03885238
delete range -0.14731355,-0.1367065 -0.055646885,-0.034432773
delete range -0.15261708,-0.1287512 0.037164867,0.04600408
delete range 0.12758602,0.1514519 -0.05741473,-0.04327199
delete range 0.037426032,0.06571152 0.1335123,0.14677113
delete range -0.0545018,-0.03770729 0.1414676,0.14411937
```

```
history unbal

history xdis 0.18357998,1.6982069E-6

history xdis -0.18362078,-1.2222274E-5

history ydis -1.735096E-5,0.18385594

history ydis -2.60994E-5,-0.18380767

history ydis 0

step 5000
```

Paper 2

Plasticity model

```
HMLP Carynginia

new
config fluid
poly tunnel rad=0.075 leng=0,5 ratr=10.0 dip=90 dd=0 nr=1 nt=1 nx=1

join on
;
jset dip 45 dd 250 spac 0.5 num 30
jset dip 45 dd 180 spac 0.5 num 30

; zoning
gen edge 0.05
def mat_prop

  bulk_modulus = 20.90e9
  Shear_modulus = 10.78e9
  rock_density = 2600
  bcoh_ = 6e6
  bten_ = 8e6
  fric_angle = 28
  dilation_angle = 0

  ;Joint properties

  joint_kn = 9e9
  joint_ks = 6e9
  j_friction = 30
  j_tension = 0.0
  j_cohesion = 0.0
  j_ap0 = 1e-4 ;aperture at 0 normal stress

  ;fluid properties
  fluid_bulk_ = 3e6
  fluid_density_ = 1000.0
  fluid_viscosity_ = 0.001

end
@mat_prop

prop mat 1 bulk @bulk_modulus g @shear_modulus dens @rock_density bcoh @bcoh_
prop mat 1 bten @bten_ phi @fric_angle psi @dilation_angle
change mat 1 cons 2
```

```
;joint material properties for initial stress state, maintain constant aperture

prop jmat 1 jkn @joint_kn jks @joint_ks jfric @j_friction
prop jmat 1 jcoh @j_cohesion jten @j_tension azero @j_ap0 ares @j_ap0 amax @j_ap0

change jmat 1
; assigning fluid properties
fluid bulk @fluid_bulk_ density @fluid_density_ viscosity @fluid_viscosity_

; insitu stress and gradients
def set_insitu
;INPUT
depth = 2780 ; m
gravity_ = 9.81 ; m3/s

KH_max = 0.818 ; ration of maximum horizontal to vertical
Kh_min = 0.788 ; ratio of minimum horizontal to vertical

; Stresses at z= 0 of the model (positive)
szz0 = -rock_density*depth*gravity_ ; Vertical stress as from paper formula -rock_density*depth*gravity_
sxx0 = KH_max*szz0
syy0 = Kh_min*szz0

; fluid pressure at z = 0 (positive)
pp0 = fluid_density_*depth*gravity_ ; if calculated by fluid_density_*depth*gravity_ = 27.5 MPa

;gradients per m in positive z direction

szz_grad = rock_density*gravity_
syy_grad = kh_min*szz_grad
sxx_grad = kH_max*szz_grad
pp_grad = -fluid_density_ * gravity_

end
@set_insitu

;in-situ stress

insitu stress @sxx0 @syy0 @szz0 0. 0. 0. &
      zgrad @sxx_grad @syy_grad @szz_grad 0. 0. 0. nodisp
;insitu pp @pp0 grad 0. 0. @pp_grad nodisp

;Boundary consitions

bound xvel 0.0 yvel 0.0 zvel 0.0 range x 0.825
bound xvel 0.0 yvel 0.0 zvel 0.0 range x -0.825
bound xvel 0.0 yvel 0.0 zvel 0.0 range z 0
bound xvel 0.0 yvel 0.0 zvel 0.0 range z -5
bound xvel 0.0 yvel 0.0 zvel 0.0 range y 0.825
bound xvel 0.0 yvel 0.0 zvel 0.0 range y -0.825

;bound stress -54e6 0 0 0,0,0 range x 0.825
;bound stress -54e6,0,0 0,0,0 range x -0.825
;bound stress 0 0 -66e6 0,0,0 range z 0
;bound stress 0 0 -66e6 0,0,0 range z -5
;bound stress 0,-52e6,0 0,0,0 range y 0.825
;bound stress 0,-52e6,0 0,0,0 range y -0.825

gravity 0 0 [-gravity_]
set flow off mech on
fluid bulk 0
hist unbal
set small
cyc 200

delete range x -0.075,0.075 y -0.075,0.075 z 0,-5
```

```
def reset_aperture
  local fp = flow_head
  loop while fp # 0
    local fpx = fp_fpx(fp)
    loop while fpx # 0
      fpx_apmech(fpx) = j_ap0
      fpx = fpx_next(fpx)
    end_loop
    fp = fp_next(fp)
  end_loop
end

def bh_setup

 ;maximum aperture
 j_ap_max = 30.0e-4
end

@bh_setup
;.....applying pressure in the borehole
bou stress -28e6 -28e6 -28e6 0.0 0.0 0.0 range cylinder end1 0,0,0 end2 0,0,-5 rad 0,0.08


;
; reset displacements, apertures and time
reset disp jdisp
@reset_aperture
set time 0

; change joint materials to allow for joint opening
prop jmat 1 amax @j_ap_max

; flow only occurs through joints that have failed
set crack_flow on

; setup general fluid properties
fluid bulk @fluid_bulk_
fluid volmin 1e-3 areamin 0.25
set flow on mech on

; maximum number of mechanical steps per fluid step
set nmech 5

; inject into center
bound disch 0.053 range x -0.075 0.075 y -0.075 0.075 z 0,-5

; Notes
;the problem is not the whole data file but method of injection
; point 1
his ndis 0.075 0.075 -2.5
his sdis 0.075 0.075 -2.5
his sstress 0.075 0.075 -2.5
his nstress 0.075 0.075 -2.5
his fluid_pp 0.075 0.075 -2.5
;point 2
his ndis -0.075 0.075 -2.5
his sdis -0.075 0.075 -2.5
his sstress -0.075 0.075 -2.5
his nstress -0.075 0.075 -2.5
his fluid_pp -0.075 0.075 -2.5
;point 3
his ndis -0.075 -0.075 -2.5
his sdis -0.075 -0.075 -2.5
his sstress -0.075 -0.075 -2.5
his nstress -0.075 -0.075 -2.5
his fluid_pp -0.075 -0.075 -2.5
;point 4
```

```
his ndis 0.075 -0.075 -2.5
his sdis 0.075 -0.075 -2.5
his sstress 0.075 -0.075 -2.5
his nstress 0.075 -0.075 -2.5
his fluid_pp 0.075 -0.075 -2.5
;point 5
his ndis 0.5 0.5 -2.5
his sdis 0.5 0.5 -2.5
his sstress 0.5 0.5 -2.5
his nstress 0.5 0.5 -2.5
his fluid_pp 0.5 0.5 -2.5
;xdis
his xdis 0.075 0.075 -2.5
his xdis -0.075 0.075 -2.5
his xdis 0.075 -0.075 -2.5
his xdis -0.075 -0.075 -2.5
his time
his unbal


cyc 1500
save HMLP-Caryngia

---------------------------------------------------

HPLM Carynginia

new
config fluid
poly tunnel rad=0.075 leng=0,5 ratr=10.0 dip=90 dd=0 nr=1 nt=1 nx=1

join on
;
jset dip 45 dd 250 spac 0.5 num 30
jset dip 45 dd 180 spac 0.5 num 30

; zoning
gen edge 0.05
def mat_prop

  bulk_modulus = 20.90e9
  Shear_modulus = 10.78e9
  rock_density = 2600
  bcoh_ = 6e6
  bten_ = 8e6
  fric_angle = 28
  dilation_angle = 0

  ;Joint properties

  joint_kn = 9e9
  joint_ks = 6e9
  j_friction = 30
  j_tension = 0.0
  j_cohesion = 0.0
  j_ap0 = 1e-4 ;aperture at 0 normal stress

  ;fluid properties
  fluid_bulk_ = 3e6
  fluid_density_ = 1000.0
  fluid_viscosity_ = 0.001

end
@mat_prop

prop mat 1 bulk @bulk_modulus g @shear_modulus dens @rock_density bcoh @bcoh_
prop mat 1 bten @bten_ phi @fric_angle psi @dilation_angle
```

```
change mat 1 cons 2

;joint material properties for initial stress state, maintain constant aperture

prop jmat 1 jkn @joint_kn jks @joint_ks jfric @j_friction
prop jmat 1 jcoh @j_cohesion jten @j_tension azero @j_ap0 ares @j_ap0 amax @j_ap0

change jmat 1
; assigning fluid properties
fluid bulk @fluid_bulk_ density @fluid_density_ viscosity @fluid_viscosity_

; insitu stress and gradients
def set_insitu
;INPUT
depth = 2780 ; m
gravity_ = 9.81 ; m3/s

KH_max = 0.818 ; ration of maximum horizontal to vertical
Kh_min = 0.788 ; ratio of minimum horizontal to vertical

; Stresses at z= 0 of the model (positive)
szz0 = -rock_density*depth*gravity_ ; Vertical stress as from paper formula -rock_density*depth*gravity_
sxx0 = KH_max*szz0
syy0 = Kh_min*szz0

; fluid pressure at z = 0 (positive)
pp0 = fluid_density_*depth*gravity_ ; if calculated by fluid_density_*depth*gravity_ = 27.5 MPa

;gradients per m in positive z direction

szz_grad = rock_density*gravity_
syy_grad = kh_min*szz_grad
sxx_grad = kH_max*szz_grad
pp_grad = -fluid_density_ * gravity_

end
@set_insitu

;in-situ stress

insitu stress @sxx0 @syy0 @szz0 0. 0. 0. &
      zgrad @sxx_grad @syy_grad @szz_grad 0. 0. 0. nodisp
insitu pp @pp0 grad 0. 0. @pp_grad nodisp

;Boundary consitions

bound xvel 0.0 yvel 0.0 zvel 0.0 range x 0.825
bound xvel 0.0 yvel 0.0 zvel 0.0 range x -0.825
bound xvel 0.0 yvel 0.0 zvel 0.0 range z 0
bound xvel 0.0 yvel 0.0 zvel 0.0 range z -5
bound xvel 0.0 yvel 0.0 zvel 0.0 range y 0.825
bound xvel 0.0 yvel 0.0 zvel 0.0 range y -0.825

;bound stress -54e6 0 0 0,0,0 range x 0.825
;bound stress -54e6,0,0 0,0,0 range x -0.825
;bound stress 0 0 -66e6 0,0,0 range z 0
;bound stress 0 0 -66e6 0,0,0 range z -5
;bound stress 0,-52e6,0 0,0,0 range y 0.825
;bound stress 0,-52e6,0 0,0,0 range y -0.825

gravity 0 0 [-gravity_]
set flow off mech on
fluid bulk 0
hist unbal
set small
cyc 200
```

```
delete range x -0.075,0.075 y -0.075,0.075 z 0,-5

def reset_aperture
  local fp = flow_head
  loop while fp # 0
    local fpx = fp_fpx(fp)
    loop while fpx # 0
      fpx_apmech(fpx) = j_ap0
      fpx = fpx_next(fpx)
    end_loop
    fp = fp_next(fp)
  end_loop
end

def bh_setup

 ;maximum aperture
 j_ap_max = 30.0e-4
end

@bh_setup
;.....applying pressure in the borehole
bou stress -28e6 -28e6 -28e6 0.0 0.0 0.0 range cylinder end1 0,0,0 end2 0,0,-5 rad 0,0.08


;
; reset displacements, apertures and time
reset disp jdisp
@reset_aperture
set time 0

; change joint materials to allow for joint opening
prop jmat 1 amax @j_ap_max

; flow only occurs through joints that have failed
set crack_flow on

; setup general fluid properties
fluid bulk @fluid_bulk_
fluid volmin 1e-3 areamin 0.25
set flow on mech on

; maximum number of mechanical steps per fluid step
set nmech 5

; inject into center
;bound disch 0.053 range x -0.075 0.075 y -0.075 0.075 z 0,-5

; Notes
;the problem is not the whole data file but method of injection
; point 1
his ndis 0.075 0.075 -2.5
his sdis 0.075 0.075 -2.5
his sstress 0.075 0.075 -2.5
his nstress 0.075 0.075 -2.5
his fluid_pp 0.075 0.075 -2.5
;point 2
his ndis -0.075 0.075 -2.5
his sdis -0.075 0.075 -2.5
his sstress -0.075 0.075 -2.5
his nstress -0.075 0.075 -2.5
his fluid_pp -0.075 0.075 -2.5
;point 3
his ndis -0.075 -0.075 -2.5
his sdis -0.075 -0.075 -2.5
his sstress -0.075 -0.075 -2.5
his nstress -0.075 -0.075 -2.5
```

```
his fluid_pp -0.075 -0.075 -2.5
;point 4
his ndis 0.075 -0.075 -2.5
his sdis 0.075 -0.075 -2.5
his sstress 0.075 -0.075 -2.5
his nstress 0.075 -0.075 -2.5
his fluid_pp 0.075 -0.075 -2.5
;point 5
his ndis 0.5 0.5 -2.5
his sdis 0.5 0.5 -2.5
his sstress 0.5 0.5 -2.5
his nstress 0.5 0.5 -2.5
his fluid_pp 0.5 0.5 -2.5
;xdis
his xdis 0.075 0.075 -2.5
his xdis -0.075 0.075 -2.5
his xdis 0.075 -0.075 -2.5
his xdis -0.075 -0.075 -2.5
his time
his unbal


cyc 1500
save HPLM-Caryngia

----------------------------------------

EQMP Carynginia

new
config fluid
poly tunnel rad=0.075 leng=0,5 ratr=10.0 dip=90 dd=0 nr=1 nt=1 nx=1

join on
;
jset dip 45 dd 250 spac 0.5 num 30
jset dip 45 dd 180 spac 0.5 num 30

; zoning
gen edge 0.05
def mat_prop

  bulk_modulus = 20.90e9
  Shear_modulus = 10.78e9
  rock_density = 2600
  bcoh_ = 6e6
  bten_ = 8e6
  fric_angle = 28
  dilation_angle = 0

  ;Joint properties

  joint_kn = 9e9
  joint_ks = 6e9
  j_friction = 30
  j_tension = 0.0
  j_cohesion = 0.0
  j_ap0 = 1e-4 ;aperture at 0 normal stress

  ;fluid properties
  fluid_bulk_ = 3e6
  fluid_density_ = 1000.0
  fluid_viscosity_ = 0.001

end
@mat_prop
```

```
prop mat 1 bulk @bulk_modulus g @shear_modulus dens @rock_density bcoh @bcoh_
prop mat 1 bten @bten_ phi @fric_angle psi @dilation_angle
change mat 1 cons 2

;joint material properties for initial stress state, maintain constant aperture

prop jmat 1 jkn @joint_kn jks @joint_ks jfric @j_friction
prop jmat 1 jcoh @j_cohesion jten @j_tension azero @j_ap0 ares @j_ap0 amax @j_ap0

change jmat 1
; assigning fluid properties
fluid bulk @fluid_bulk_ density @fluid_density_ viscosity @fluid_viscosity_

; insitu stress and gradients
def set_insitu
;INPUT
depth = 2780 ; m
gravity_ = 9.81 ; m3/s

KH_max = 0.818 ; ration of maximum horizontal to vertical
Kh_min = 0.788 ; ratio of minimum horizontal to vertical

; Stresses at z= 0 of the model (positive)
szz0 = -rock_density*depth*gravity_ ; Vertical stress as from paper formula -rock_density*depth*gravity_
sxx0 = KH_max*szz0
syy0 = Kh_min*szz0

; fluid pressure at z = 0 (positive)
pp0 = fluid_density_*depth*gravity_ ; if calculated by fluid_density_*depth*gravity_ = 27.5 MPa

;gradients per m in positive z direction

szz_grad = rock_density*gravity_
syy_grad = kh_min*szz_grad
sxx_grad = kH_max*szz_grad
pp_grad = -fluid_density_ * gravity_

end
@set_insitu

;in-situ stress

insitu stress @sxx0 @syy0 @szz0 0. 0. 0. &
      zgrad @sxx_grad @syy_grad @szz_grad 0. 0. 0. nodisp
insitu pp @pp0 grad 0. 0. @pp_grad nodisp

;Boundary consitions

bound xvel 0.0 yvel 0.0 zvel 0.0 range x 0.825
bound xvel 0.0 yvel 0.0 zvel 0.0 range x -0.825
bound xvel 0.0 yvel 0.0 zvel 0.0 range z 0
bound xvel 0.0 yvel 0.0 zvel 0.0 range z -5
bound xvel 0.0 yvel 0.0 zvel 0.0 range y 0.825
bound xvel 0.0 yvel 0.0 zvel 0.0 range y -0.825

;bound stress -54e6 0 0 0,0,0 range x 0.825
;bound stress -54e6,0,0 0,0,0 range x -0.825
;bound stress 0 0 -66e6 0,0,0 range z 0
;bound stress 0 0 -66e6 0,0,0 range z -5
;bound stress 0,-52e6,0 0,0,0 range y 0.825
;bound stress 0,-52e6,0 0,0,0 range y -0.825

gravity 0 0 [-gravity_]
set flow off mech on
fluid bulk 0
hist unbal
set small
```

```
cyc 200

delete range x -0.075,0.075 y -0.075,0.075 z 0,-5

def reset_aperture
  local fp = flow_head
  loop while fp # 0
    local fpx = fp_fpx(fp)
    loop while fpx # 0
      fpx_apmech(fpx) = j_ap0
      fpx = fpx_next(fpx)
    end_loop
    fp = fp_next(fp)
  end_loop
end

def bh_setup

 ;maximum aperture
 j_ap_max = 30.0e-4
end

@bh_setup
;.....applying pressure in the borehole
bou stress -28e6 -28e6 -28e6 0.0 0.0 0.0 range cylinder end1 0,0,0 end2 0,0,-5 rad 0,0.08


;
; reset displacements, apertures and time
reset disp jdisp
@reset_aperture
set time 0

; change joint materials to allow for joint opening
prop jmat 1 amax @j_ap_max

; flow only occurs through joints that have failed
set crack_flow on

; setup general fluid properties
fluid bulk @fluid_bulk_
fluid volmin 1e-3 areamin 0.25
set flow on mech on

; maximum number of mechanical steps per fluid step
set nmech 5

; inject into center
bound disch 0.0001 range x -0.075 0.075 y -0.075 0.075 z 0,-5

; Notes
;the problem is not the whole data file but method of injection
; point 1
his ndis 0.075 0.075 -2.5
his sdis 0.075 0.075 -2.5
his sstress 0.075 0.075 -2.5
his nstress 0.075 0.075 -2.5
his fluid_pp 0.075 0.075 -2.5
;point 2
his ndis -0.075 0.075 -2.5
his sdis -0.075 0.075 -2.5
his sstress -0.075 0.075 -2.5
his nstress -0.075 0.075 -2.5
his fluid_pp -0.075 0.075 -2.5
;point 3
his ndis -0.075 -0.075 -2.5
his sdis -0.075 -0.075 -2.5
```

```
his sstress -0.075 -0.075 -2.5
his nstress -0.075 -0.075 -2.5
his fluid_pp -0.075 -0.075 -2.5
;point 4
his ndis 0.075 -0.075 -2.5
his sdis 0.075 -0.075 -2.5
his sstress 0.075 -0.075 -2.5
his nstress 0.075 -0.075 -2.5
his fluid_pp 0.075 -0.075 -2.5
;point 5
his ndis 0.5 0.5 -2.5
his sdis 0.5 0.5 -2.5
his sstress 0.5 0.5 -2.5
his nstress 0.5 0.5 -2.5
his fluid_pp 0.5 0.5 -2.5
;xdis
his xdis 0.075 0.075 -2.5
his xdis -0.075 0.075 -2.5
his xdis 0.075 -0.075 -2.5
his xdis -0.075 -0.075 -2.5
his time
his unbal


cyc 1500
save EQMP-Caryngia
-------------------------------------------------
```

Dry carynginia

```
new
config fluid
poly tunnel rad=0.075 leng=0,5 ratr=10.0 dip=90 dd=0 nr=1 nt=1 nx=1

join on
;
jset dip 45 dd 250 spac 0.5 num 30
jset dip 45 dd 180 spac 0.5 num 30

; zoning
gen edge 0.05
def mat_prop

  bulk_modulus = 20.90e9
  Shear_modulus = 10.78e9
  rock_density = 2600
  bcoh_ = 6e6
  bten_ = 8e6
  fric_angle = 28
  dilation_angle = 0

  ;Joint properties

  joint_kn = 9e9
  joint_ks = 6e9
  j_friction = 30
  j_tension = 0.0
  j_cohesion = 0.0
  j_ap0 = 1e-4 ;aperture at 0 normal stress

  ;fluid properties
  fluid_bulk_ = 3e6
  fluid_density_ = 1000.0
  fluid_viscosity_ = 0.001

end
@mat_prop
```

```
prop mat 1 bulk @bulk_modulus g @shear_modulus dens @rock_density bcoh @bcoh_
prop mat 1 bten @bten_ phi @fric_angle psi @dilation_angle
change mat 1 cons 2

;joint material properties for initial stress state, maintain constant aperture

prop jmat 1 jkn @joint_kn jks @joint_ks jfric @j_friction
prop jmat 1 jcoh @j_cohesion jten @j_tension azero @j_ap0 ares @j_ap0 amax @j_ap0

change jmat 1
; assigning fluid properties
fluid bulk @fluid_bulk_ density @fluid_density_ viscosity @fluid_viscosity_

; insitu stress and gradients
def set_insitu
;INPUT
depth = 2780 ; m
gravity_ = 9.81 ; m3/s

KH_max = 0.818 ; ration of maximum horizontal to vertical
Kh_min = 0.788 ; ratio of minimum horizontal to vertical

; Stresses at z= 0 of the model (positive)
szz0 = -rock_density*depth*gravity_ ; Vertical stress as from paper formula -rock_density*depth*gravity_
sxx0 = KH_max*szz0
syy0 = Kh_min*szz0

; fluid pressure at z = 0 (positive)
pp0 = fluid_density_*depth*gravity_ ; if calculated by fluid_density_*depth*gravity_ = 27.5 MPa

;gradients per m in positive z direction

szz_grad = rock_density*gravity_
syy_grad = kh_min*szz_grad
sxx_grad = kH_max*szz_grad
pp_grad = -fluid_density_ * gravity_

end
@set_insitu

;in-situ stress

insitu stress @sxx0 @syy0 @szz0 0. 0. 0. &
      zgrad @sxx_grad @syy_grad @szz_grad 0. 0. 0. nodisp
;insitu pp @pp0 grad 0. 0. @pp_grad nodisp

;Boundary consitions

bound xvel 0.0 yvel 0.0 zvel 0.0 range x 0.825
bound xvel 0.0 yvel 0.0 zvel 0.0 range x -0.825
bound xvel 0.0 yvel 0.0 zvel 0.0 range z 0
bound xvel 0.0 yvel 0.0 zvel 0.0 range z -5
bound xvel 0.0 yvel 0.0 zvel 0.0 range y 0.825
bound xvel 0.0 yvel 0.0 zvel 0.0 range y -0.825

;bound stress -54e6 0 0 0,0,0 range x 0.825
;bound stress -54e6,0,0 0,0,0 range x -0.825
;bound stress 0 0 -66e6 0,0,0 range z 0
;bound stress 0 0 -66e6 0,0,0 range z -5
;bound stress 0,-52e6,0 0,0,0 range y 0.825
;bound stress 0,-52e6,0 0,0,0 range y -0.825

gravity 0 0 [-gravity_]
set flow off mech on
fluid bulk 0
hist unbal
```

```
set small
cyc 200

delete range x -0.075,0.075 y -0.075,0.075 z 0,-5

def reset_aperture
  local fp = flow_head
  loop while fp # 0
    local fpx = fp_fpx(fp)
    loop while fpx # 0
      fpx_apmech(fpx) = j_ap0
      fpx = fpx_next(fpx)
    end_loop
    fp = fp_next(fp)
  end_loop
end

def bh_setup

 ;maximum aperture
 j_ap_max = 30.0e-4
end

@bh_setup
;.....applying pressure in the borehole
bou stress -28e6 -28e6 -28e6 0.0 0.0 0.0 range cylinder end1 0,0,0 end2 0,0,-5 rad 0,0.08


;
; reset displacements, apertures and time
reset disp jdisp
@reset_aperture
set time 0

; change joint materials to allow for joint opening
prop jmat 1 amax @j_ap_max

; flow only occurs through joints that have failed
set crack_flow on

; setup general fluid properties
fluid bulk @fluid_bulk_
fluid volmin 1e-3 areamin 0.25
set flow on mech on

; maximum number of mechanical steps per fluid step
set nmech 5

; inject into center
;bound disch 0.0001 range x -0.075 0.075 y -0.075 0.075 z 0,-5

; Notes
;the problem is not the whole data file but method of injection
; point 1
his ndis 0.075 0.075 -2.5
his sdis 0.075 0.075 -2.5
his sstress 0.075 0.075 -2.5
his nstress 0.075 0.075 -2.5
his fluid_pp 0.075 0.075 -2.5
;point 2
his ndis -0.075 0.075 -2.5
his sdis -0.075 0.075 -2.5
his sstress -0.075 0.075 -2.5
his nstress -0.075 0.075 -2.5
his fluid_pp -0.075 0.075 -2.5
;point 3
his ndis -0.075 -0.075 -2.5
```

```
his sdis -0.075 -0.075 -2.5
his sstress -0.075 -0.075 -2.5
his nstress -0.075 -0.075 -2.5
his fluid_pp -0.075 -0.075 -2.5
;point 4
his ndis 0.075 -0.075 -2.5
his sdis 0.075 -0.075 -2.5
his sstress 0.075 -0.075 -2.5
his nstress 0.075 -0.075 -2.5
his fluid_pp 0.075 -0.075 -2.5
;point 5
his ndis 0.5 0.5 -2.5
his sdis 0.5 0.5 -2.5
his sstress 0.5 0.5 -2.5
his nstress 0.5 0.5 -2.5
his fluid_pp 0.5 0.5 -2.5
;xdis
his xdis 0.075 0.075 -2.5
his xdis -0.075 0.075 -2.5
his xdis 0.075 -0.075 -2.5
his xdis -0.075 -0.075 -2.5
his time
his unbal


cyc 1500
save dry-caryngia
---------------------------------------
```

High Cliff sandstone

HMLP High Cliff

```
new
config fluid
poly tunnel rad=0.075 leng=0,5 ratr=10.0 dip=90 dd=0 nr=1 nt=1 nx=1

join on
;
jset dip 45 dd 250 spac 0.5 num 30
jset dip 45 dd 180 spac 0.5 num 30

; zoning
gen edge 0.05
def mat_prop

bulk_modulus = 30.55e9
Shear_modulus = 22.9e9
rock_density = 2550
bcoh_ = 13e6
bten_ = 10.7e6
fric_angle = 46
dilation_angle = 11.5

;Joint properties

joint_kn = 9e9
joint_ks = 6e9
j_friction = 30
j_tension = 0.0
j_cohesion = 0.0
j_ap0 = 1e-4 ;aperture at 0 normal stress

;fluid properties
fluid_bulk_ = 3e6
fluid_density_ = 1000.0
```

```
fluid_viscosity_ = 0.001

end
@mat_prop

prop mat 1 bulk @bulk_modulus g @shear_modulus dens @rock_density bcoh @bcoh_
prop mat 1 bten @bten_ phi @fric_angle psi @dilation_angle
change mat 1 cons 2

;joint material properties for initial stress state, maintain constant aperture

prop jmat 1 jkn @joint_kn jks @joint_ks jfric @j_friction
prop jmat 1 jcoh @j_cohesion jten @j_tension azero @j_ap0 ares @j_ap0 amax @j_ap0

change jmat 1
; assigning fluid properties
fluid bulk @fluid_bulk_ density @fluid_density_ viscosity @fluid_viscosity_

; insitu stress and gradients
def set_insitu
;INPUT
depth = 3270 ; m
gravity_ = 9.81 ; m3/s

KH_max = 0.818 ; ration of maximum horizontal to vertical
Kh_min = 0.788 ; ratio of minimum horizontal to vertical

; Stresses at z= 0 of the model (positive)
szz0 = -rock_density*depth*gravity_ ; Vertical stress as from paper formula -rock_density*depth*gravity_
sxx0 = KH_max*szz0
syy0 = Kh_min*szz0

; fluid pressure at z = 0 (positive)
pp0 = fluid_density_*depth*gravity_ ; if calculated by fluid_density_*depth*gravity_ = 27.5 MPa

;gradients per m in positive z direction

szz_grad = rock_density*gravity_
syy_grad = kh_min*szz_grad
sxx_grad = kH_max*szz_grad
pp_grad = -fluid_density_ * gravity_

end
@set_insitu

;in-situ stress

insitu stress @sxx0 @syy0 @szz0 0. 0. 0. &
zgrad @sxx_grad @syy_grad @szz_grad 0. 0. 0. nodisp
;insitu pp @pp0 grad 0. 0. @pp_grad nodisp

;Boundary consitions

bound xvel 0.0 yvel 0.0 zvel 0.0 range x 0.825
bound xvel 0.0 yvel 0.0 zvel 0.0 range x -0.825
bound xvel 0.0 yvel 0.0 zvel 0.0 range z 0
bound xvel 0.0 yvel 0.0 zvel 0.0 range z -5
bound xvel 0.0 yvel 0.0 zvel 0.0 range y 0.825
bound xvel 0.0 yvel 0.0 zvel 0.0 range y -0.825

;bound stress -54e6 0 0 0,0,0 range x 0.825
;bound stress -54e6,0,0 0,0,0 range x -0.825
;bound stress 0 0 -66e6 0,0,0 range z 0
;bound stress 0 0 -66e6 0,0,0 range z -5
;bound stress 0,-52e6,0 0,0,0 range y 0.825
;bound stress 0,-52e6,0 0,0,0 range y -0.825
```

```
gravity 0 0 [-gravity_]
set flow off mech on
fluid bulk 0
hist unbal
set small
cyc 200

delete range x -0.075,0.075 y -0.075,0.075 z 0,-5

def reset_aperture
local fp = flow_head
loop while fp # 0
local fpx = fp_fpx(fp)
loop while fpx # 0
fpx_apmech(fpx) = j_ap0
fpx = fpx_next(fpx)
end_loop
fp = fp_next(fp)
end_loop
end

def bh_setup

;maximum aperture
j_ap_max = 30.0e-4
end

@bh_setup
;.....applying pressure in the borehole
bou stress -28e6 -28e6 -28e6 0.0 0.0 0.0 range cylinder end1 0,0,0 end2 0,0,-5 rad 0,0.08


;
; reset displacements, apertures and time
reset disp jdisp
@reset_aperture
set time 0

; change joint materials to allow for joint opening
prop jmat 1 amax @j_ap_max

; flow only occurs through joints that have failed
set crack_flow on

; setup general fluid properties
fluid bulk @fluid_bulk_
fluid volmin 1e-3 areamin 0.25
set flow on mech on

; maximum number of mechanical steps per fluid step
set nmech 5

; inject into center
bound disch 0.053 range x -0.075 0.075 y -0.075 0.075 z 0,-5

; Notes
;the problem is not the whole data file but method of injection
; point 1
his ndis 0.075 0.075 -2.5
his sdis 0.075 0.075 -2.5
his sstress 0.075 0.075 -2.5
his nstress 0.075 0.075 -2.5
his fluid_pp 0.075 0.075 -2.5
;point 2
his ndis -0.075 0.075 -2.5
his sdis -0.075 0.075 -2.5
his sstress -0.075 0.075 -2.5
```

```
his nstress -0.075 0.075 -2.5
his fluid_pp -0.075 0.075 -2.5
;point 3
his ndis -0.075 -0.075 -2.5
his sdis -0.075 -0.075 -2.5
his sstress -0.075 -0.075 -2.5
his nstress -0.075 -0.075 -2.5
his fluid_pp -0.075 -0.075 -2.5
;point 4
his ndis 0.075 -0.075 -2.5
his sdis 0.075 -0.075 -2.5
his sstress 0.075 -0.075 -2.5
his nstress 0.075 -0.075 -2.5
his fluid_pp 0.075 -0.075 -2.5
;point 5
his ndis 0.5 0.5 -2.5
his sdis 0.5 0.5 -2.5
his sstress 0.5 0.5 -2.5
his nstress 0.5 0.5 -2.5
his fluid_pp 0.5 0.5 -2.5
;xdis
his xdis 0.075 0.075 -2.5
his xdis -0.075 0.075 -2.5
his xdis 0.075 -0.075 -2.5
his xdis -0.075 -0.075 -2.5
his time
his unbal


cyc 1500
save High-cliff
```

HPLM High Cliff

```
new
config fluid
poly tunnel rad=0.075 leng=0,5 ratr=10.0 dip=90 dd=0 nr=1 nt=1 nx=1

join on
;
jset dip 45 dd 250 spac 0.5 num 30
jset dip 45 dd 180 spac 0.5 num 30

; zoning
gen edge 0.05
def mat_prop

bulk_modulus = 30.55e9
Shear_modulus = 22.9e9
rock_density = 2550
bcoh_ = 13e6
bten_ = 10.7e6
fric_angle = 46
dilation_angle = 11.5

;Joint properties

joint_kn = 9e9
joint_ks = 6e9
j_friction = 30
j_tension = 0.0
j_cohesion = 0.0
j_ap0 = 1e-4 ;aperture at 0 normal stress

;fluid properties
```

```
fluid_bulk_ = 3e6
fluid_density_ = 1000.0
fluid_viscosity_ = 0.001

end
@mat_prop

prop mat 1 bulk @bulk_modulus g @shear_modulus dens @rock_density bcoh @bcoh_
prop mat 1 bten @bten_ phi @fric_angle psi @dilation_angle
change mat 1 cons 2

;joint material properties for initial stress state, maintain constant aperture

prop jmat 1 jkn @joint_kn jks @joint_ks jfric @j_friction
prop jmat 1 jcoh @j_cohesion jten @j_tension azero @j_ap0 ares @j_ap0 amax @j_ap0

change jmat 1
; assigning fluid properties
fluid bulk @fluid_bulk_ density @fluid_density_ viscosity @fluid_viscosity_

; insitu stress and gradients
def set_insitu
;INPUT
depth = 3270 ; m
gravity_ = 9.81 ; m3/s

KH_max = 0.818 ; ration of maximum horizontal to vertical
Kh_min = 0.788 ; ratio of minimum horizontal to vertical

; Stresses at z= 0 of the model (positive)
szz0 = -rock_density*depth*gravity_ ; Vertical stress as from paper formula -rock_density*depth*gravity_
sxx0 = KH_max*szz0
syy0 = Kh_min*szz0

; fluid pressure at z = 0 (positive)
pp0 = fluid_density_*depth*gravity_ ; if calculated by fluid_density_*depth*gravity_ = 27.5 MPa

;gradients per m in positive z direction

szz_grad = rock_density*gravity_
syy_grad = kh_min*szz_grad
sxx_grad = kH_max*szz_grad
pp_grad = -fluid_density_ * gravity_

end
@set_insitu

;in-situ stress

insitu stress @sxx0 @syy0 @szz0 0. 0. 0. &
zgrad @sxx_grad @syy_grad @szz_grad 0. 0. 0. nodisp
insitu pp @pp0 grad 0. 0. @pp_grad nodisp

;Boundary consitions

bound xvel 0.0 yvel 0.0 zvel 0.0 range x 0.825
bound xvel 0.0 yvel 0.0 zvel 0.0 range x -0.825
bound xvel 0.0 yvel 0.0 zvel 0.0 range z 0
bound xvel 0.0 yvel 0.0 zvel 0.0 range z -5
bound xvel 0.0 yvel 0.0 zvel 0.0 range y 0.825
bound xvel 0.0 yvel 0.0 zvel 0.0 range y -0.825

;bound stress -54e6 0 0 0,0,0 range x 0.825
;bound stress -54e6,0,0 0,0,0 range x -0.825
;bound stress 0 0 -66e6 0,0,0 range z 0
;bound stress 0 0 -66e6 0,0,0 range z -5
;bound stress 0,-52e6,0 0,0,0 range y 0.825
```

```
;bound stress 0,-52e6,0 0,0,0 range y -0.825

gravity 0 0 [-gravity_]
set flow off mech on
fluid bulk 0
hist unbal
set small
cyc 200

delete range x -0.075,0.075 y -0.075,0.075 z 0,-5

def reset_aperture
local fp = flow_head
loop while fp # 0
local fpx = fp_fpx(fp)
loop while fpx # 0
fpx_apmech(fpx) = j_ap0
fpx = fpx_next(fpx)
end_loop
fp = fp_next(fp)
end_loop
end

def bh_setup

;maximum aperture
j_ap_max = 30.0e-4
end

@bh_setup
;.....applying pressure in the borehole
bou stress -28e6 -28e6 -28e6 0.0 0.0 0.0 range cylinder end1 0,0,0 end2 0,0,-5 rad 0,0.08


;
; reset displacements, apertures and time
reset disp jdisp
@reset_aperture
set time 0

; change joint materials to allow for joint opening
prop jmat 1 amax @j_ap_max

; flow only occurs through joints that have failed
set crack_flow on

; setup general fluid properties
fluid bulk @fluid_bulk_
fluid volmin 1e-3 areamin 0.25
set flow on mech on

; maximum number of mechanical steps per fluid step
set nmech 5

; inject into center
;bound disch 0.053 range x -0.075 0.075 y -0.075 0.075 z 0,-5

; Notes
;the problem is not the whole data file but method of injection
; point 1
his ndis 0.075 0.075 -2.5
his sdis 0.075 0.075 -2.5
his sstress 0.075 0.075 -2.5
his nstress 0.075 0.075 -2.5
his fluid_pp 0.075 0.075 -2.5
;point 2
his ndis -0.075 0.075 -2.5
```

```
his sdis -0.075 0.075 -2.5
his sstress -0.075 0.075 -2.5
his nstress -0.075 0.075 -2.5
his fluid_pp -0.075 0.075 -2.5
;point 3
his ndis -0.075 -0.075 -2.5
his sdis -0.075 -0.075 -2.5
his sstress -0.075 -0.075 -2.5
his nstress -0.075 -0.075 -2.5
his fluid_pp -0.075 -0.075 -2.5
;point 4
his ndis 0.075 -0.075 -2.5
his sdis 0.075 -0.075 -2.5
his sstress 0.075 -0.075 -2.5
his nstress 0.075 -0.075 -2.5
his fluid_pp 0.075 -0.075 -2.5
;point 5
his ndis 0.5 0.5 -2.5
his sdis 0.5 0.5 -2.5
his sstress 0.5 0.5 -2.5
his nstress 0.5 0.5 -2.5
his fluid_pp 0.5 0.5 -2.5
;xdis
his xdis 0.075 0.075 -2.5
his xdis -0.075 0.075 -2.5
his xdis 0.075 -0.075 -2.5
his xdis -0.075 -0.075 -2.5
his time
his unbal


cyc 1500
save HPLM-High-cliff
```

EQMP High Cliff

```
new
config fluid
poly tunnel rad=0.075 leng=0,5 ratr=10.0 dip=90 dd=0 nr=1 nt=1 nx=1

join on
;
jset dip 45 dd 250 spac 0.5 num 30
jset dip 45 dd 180 spac 0.5 num 30

; zoning
gen edge 0.05
def mat_prop

bulk_modulus = 30.55e9
Shear_modulus = 22.9e9
rock_density = 2550
bcoh_ = 13e6
bten_ = 10.7e6
fric_angle = 46
dilation_angle = 11.5

;Joint properties

joint_kn = 9e9
joint_ks = 6e9
j_friction = 30
j_tension = 0.0
j_cohesion = 0.0
j_ap0 = 1e-4 ;aperture at 0 normal stress
```

```
;fluid properties
fluid_bulk_ = 3e6
fluid_density_ = 1000.0
fluid_viscosity_ = 0.001

end
@mat_prop

prop mat 1 bulk @bulk_modulus g @shear_modulus dens @rock_density bcoh @bcoh_
prop mat 1 bten @bten_ phi @fric_angle psi @dilation_angle
change mat 1 cons 2

;joint material properties for initial stress state, maintain constant aperture

prop jmat 1 jkn @joint_kn jks @joint_ks jfric @j_friction
prop jmat 1 jcoh @j_cohesion jten @j_tension azero @j_ap0 ares @j_ap0 amax @j_ap0

change jmat 1
; assigning fluid properties
fluid bulk @fluid_bulk_ density @fluid_density_ viscosity @fluid_viscosity_

; insitu stress and gradients
def set_insitu
;INPUT
depth = 3270 ; m
gravity_ = 9.81 ; m3/s

KH_max = 0.818 ; ration of maximum horizontal to vertical
Kh_min = 0.788 ; ratio of minimum horizontal to vertical

; Stresses at z= 0 of the model (positive)
szz0 = -rock_density*depth*gravity_ ; Vertical stress as from paper formula -rock_density*depth*gravity_
sxx0 = KH_max*szz0
syy0 = Kh_min*szz0

; fluid pressure at z = 0 (positive)
pp0 = fluid_density_*depth*gravity_ ; if calculated by fluid_density_*depth*gravity_ = 27.5 MPa

;gradients per m in positive z direction

szz_grad = rock_density*gravity_
syy_grad = kh_min*szz_grad
sxx_grad = kH_max*szz_grad
pp_grad = -fluid_density_ * gravity_

end
@set_insitu

;in-situ stress

insitu stress @sxx0 @syy0 @szz0 0. 0. 0. &
zgrad @sxx_grad @syy_grad @szz_grad 0. 0. 0. nodisp
insitu pp @pp0 grad 0. 0. @pp_grad nodisp

;Boundary consitions

bound xvel 0.0 yvel 0.0 zvel 0.0 range x 0.825
bound xvel 0.0 yvel 0.0 zvel 0.0 range x -0.825
bound xvel 0.0 yvel 0.0 zvel 0.0 range z 0
bound xvel 0.0 yvel 0.0 zvel 0.0 range z -5
bound xvel 0.0 yvel 0.0 zvel 0.0 range y 0.825
bound xvel 0.0 yvel 0.0 zvel 0.0 range y -0.825

;bound stress -54e6 0 0 0,0,0 range x 0.825
;bound stress -54e6,0,0 0,0,0 range x -0.825
;bound stress 0 0 -66e6 0,0,0 range z 0
```

```
;bound stress 0 0 -66e6 0,0,0 range z -5
;bound stress 0,-52e6,0 0,0,0 range y 0.825
;bound stress 0,-52e6,0 0,0,0 range y -0.825

gravity 0 0 [-gravity_]
set flow off mech on
fluid bulk 0
hist unbal
set small
cyc 200

delete range x -0.075,0.075 y -0.075,0.075 z 0,-5

def reset_aperture
local fp = flow_head
loop while fp # 0
local fpx = fp_fpx(fp)
loop while fpx # 0
fpx_apmech(fpx) = j_ap0
fpx = fpx_next(fpx)
end_loop
fp = fp_next(fp)
end_loop
end

def bh_setup

;maximum aperture
j_ap_max = 30.0e-4
end

@bh_setup
;.....applying pressure in the borehole
bou stress -28e6 -28e6 -28e6 0.0 0.0 0.0 range cylinder end1 0,0,0 end2 0,0,-5 rad 0,0.08


;
; reset displacements, apertures and time
reset disp jdisp
@reset_aperture
set time 0

; change joint materials to allow for joint opening
prop jmat 1 amax @j_ap_max

; flow only occurs through joints that have failed
set crack_flow on

; setup general fluid properties
fluid bulk @fluid_bulk_
fluid volmin 1e-3 areamin 0.25
set flow on mech on

; maximum number of mechanical steps per fluid step
set nmech 5

; inject into center
bound disch 0.0001 range x -0.075 0.075 y -0.075 0.075 z 0,-5

; Notes-injection method
; point 1
his ndis 0.075 0.075 -2.5
his sdis 0.075 0.075 -2.5
his sstress 0.075 0.075 -2.5
his nstress 0.075 0.075 -2.5
his fluid_pp 0.075 0.075 -2.5
;point 2
```

```
his ndis -0.075 0.075 -2.5
his sdis -0.075 0.075 -2.5
his sstress -0.075 0.075 -2.5
his nstress -0.075 0.075 -2.5
his fluid_pp -0.075 0.075 -2.5
;point 3
his ndis -0.075 -0.075 -2.5
his sdis -0.075 -0.075 -2.5
his sstress -0.075 -0.075 -2.5
his nstress -0.075 -0.075 -2.5
his fluid_pp -0.075 -0.075 -2.5
;point 4
his ndis 0.075 -0.075 -2.5
his sdis 0.075 -0.075 -2.5
his sstress 0.075 -0.075 -2.5
his nstress 0.075 -0.075 -2.5
his fluid_pp 0.075 -0.075 -2.5
;point 5
his ndis 0.5 0.5 -2.5
his sdis 0.5 0.5 -2.5
his sstress 0.5 0.5 -2.5
his nstress 0.5 0.5 -2.5
his fluid_pp 0.5 0.5 -2.5
;xdis
his xdis 0.075 0.075 -2.5
his xdis -0.075 0.075 -2.5
his xdis 0.075 -0.075 -2.5
his xdis -0.075 -0.075 -2.5
his time
his unbal


cyc 1500
save EQMP-High-cliff

--------------------------------------
```

Dry High Cliff

```
new
config fluid
poly tunnel rad=0.075 leng=0,5 ratr=10.0 dip=90 dd=0 nr=1 nt=1 nx=1

join on
;
jset dip 45 dd 250 spac 0.5 num 30
jset dip 45 dd 180 spac 0.5 num 30

; zoning
gen edge 0.05
def mat_prop

bulk_modulus = 30.55e9
Shear_modulus = 22.9e9
rock_density = 2550
bcoh_ = 13e6
bten_ = 10.7e6
fric_angle = 46
dilation_angle = 11.5

;Joint properties

joint_kn = 9e9
joint_ks = 6e9
j_friction = 30
j_tension = 0.0
j_cohesion = 0.0
```

```
j_ap0 = 1e-4 ;aperture at 0 normal stress

;fluid properties
fluid_bulk_ = 3e6
fluid_density_ = 1000.0
fluid_viscosity_ = 0.001

end
@mat_prop

prop mat 1 bulk @bulk_modulus g @shear_modulus dens @rock_density bcoh @bcoh_
prop mat 1 bten @bten_ phi @fric_angle psi @dilation_angle
change mat 1 cons 2

;joint material properties for initial stress state, maintain constant aperture

prop jmat 1 jkn @joint_kn jks @joint_ks jfric @j_friction
prop jmat 1 jcoh @j_cohesion jten @j_tension azero @j_ap0 ares @j_ap0 amax @j_ap0

change jmat 1
; assigning fluid properties
fluid bulk @fluid_bulk_ density @fluid_density_ viscosity @fluid_viscosity_

; insitu stress and gradients
def set_insitu
;INPUT
depth = 3270 ; m
gravity_ = 9.81 ; m3/s

KH_max = 0.818 ; ration of maximum horizontal to vertical
Kh_min = 0.788 ; ratio of minimum horizontal to vertical

; Stresses at z= 0 of the model (positive)
szz0 = -rock_density*depth*gravity_ ; Vertical stress as from paper formula -rock_density*depth*gravity_
sxx0 = KH_max*szz0
syy0 = Kh_min*szz0

; fluid pressure at z = 0 (positive)
pp0 = fluid_density_*depth*gravity_ ; if calculated by fluid_density_*depth*gravity_ = 27.5 MPa

;gradients per m in positive z direction

szz_grad = rock_density*gravity_
syy_grad = kh_min*szz_grad
sxx_grad = kH_max*szz_grad
pp_grad = -fluid_density_ * gravity_

end
@set_insitu

;in-situ stress

insitu stress @sxx0 @syy0 @szz0 0. 0. 0. &
zgrad @sxx_grad @syy_grad @szz_grad 0. 0. 0. nodisp
;insitu pp @pp0 grad 0. 0. @pp_grad nodisp

;Boundary consitions

bound xvel 0.0 yvel 0.0 zvel 0.0 range x 0.825
bound xvel 0.0 yvel 0.0 zvel 0.0 range x -0.825
bound xvel 0.0 yvel 0.0 zvel 0.0 range z 0
bound xvel 0.0 yvel 0.0 zvel 0.0 range z -5
bound xvel 0.0 yvel 0.0 zvel 0.0 range y 0.825
bound xvel 0.0 yvel 0.0 zvel 0.0 range y -0.825

;bound stress -54e6 0 0 0,0,0 range x 0.825
;bound stress -54e6,0,0 0,0,0 range x -0.825
```

```
;bound stress 0 0 -66e6 0,0,0 range z 0
;bound stress 0 0 -66e6 0,0,0 range z -5
;bound stress 0,-52e6,0 0,0,0 range y 0.825
;bound stress 0,-52e6,0 0,0,0 range y -0.825

gravity 0 0 [-gravity_]
set flow off mech on
fluid bulk 0
hist unbal
set small
cyc 200

delete range x -0.075,0.075 y -0.075,0.075 z 0,-5

def reset_aperture
local fp = flow_head
loop while fp # 0
local fpx = fp_fpx(fp)
loop while fpx # 0
fpx_apmech(fpx) = j_ap0
fpx = fpx_next(fpx)
end_loop
fp = fp_next(fp)
end_loop
end

def bh_setup

;maximum aperture
j_ap_max = 30.0e-4
end

@bh_setup
;.....applying pressure in the borehole
bou stress -28e6 -28e6 -28e6 0.0 0.0 0.0 range cylinder end1 0,0,0 end2 0,0,-5 rad 0,0.08


;
; reset displacements, apertures and time
reset disp jdisp
@reset_aperture
set time 0

; change joint materials to allow for joint opening
prop jmat 1 amax @j_ap_max

; flow only occurs through joints that have failed
set crack_flow on

; setup general fluid properties
fluid bulk @fluid_bulk_
fluid volmin 1e-3 areamin 0.25
set flow on mech on

; maximum number of mechanical steps per fluid step
set nmech 5

; inject into center
;bound disch 0.053 range x -0.075 0.075 y -0.075 0.075 z 0,-5

; Notes
;the problem is not the whole data file but method of injection
; point 1
his ndis 0.075 0.075 -2.5
his sdis 0.075 0.075 -2.5
his sstress 0.075 0.075 -2.5
his nstress 0.075 0.075 -2.5
```

```
his fluid_pp 0.075 0.075 -2.5
;point 2
his ndis -0.075 0.075 -2.5
his sdis -0.075 0.075 -2.5
his sstress -0.075 0.075 -2.5
his nstress -0.075 0.075 -2.5
his fluid_pp -0.075 0.075 -2.5
;point 3
his ndis -0.075 -0.075 -2.5
his sdis -0.075 -0.075 -2.5
his sstress -0.075 -0.075 -2.5
his nstress -0.075 -0.075 -2.5
his fluid_pp -0.075 -0.075 -2.5
;point 4
his ndis 0.075 -0.075 -2.5
his sdis 0.075 -0.075 -2.5
his sstress 0.075 -0.075 -2.5
his nstress 0.075 -0.075 -2.5
his fluid_pp 0.075 -0.075 -2.5
;point 5
his ndis 0.5 0.5 -2.5
his sdis 0.5 0.5 -2.5
his sstress 0.5 0.5 -2.5
his nstress 0.5 0.5 -2.5
his fluid_pp 0.5 0.5 -2.5
;xdis
his xdis 0.075 0.075 -2.5
his xdis -0.075 0.075 -2.5
his xdis 0.075 -0.075 -2.5
his xdis -0.075 -0.075 -2.5
his time
his unbal


cyc 1500
save dry-high-cliff
```

Irwin River

HMLP Irwin

```
new
config fluid
poly tunnel rad=0.075 leng=0,5 ratr=10.0 dip=90 dd=0 nr=1 nt=1 nx=1

join on
;
jset dip 45 dd 250 spac 0.5 num 30
jset dip 45 dd 180 spac 0.5 num 30

; zoning
gen edge 0.05
def mat_prop

  bulk_modulus = 18.18e9
  Shear_modulus = 9.4e9
  rock_density = 2580
  bcoh_ = 3.55e6
  bten_ = 1e6
  fric_angle = 24
  dilation_angle = 0

  ;Joint properties

  joint_kn = 9e9
```

```
  joint_ks = 6e9
  j_friction = 30
  j_tension = 0.0
  j_cohesion = 0.0
  j_ap0 = 1e-4 ;aperture at 0 normal stress

  ;fluid properties
  fluid_bulk_ = 3e6
  fluid_density_ = 1000.0
  fluid_viscosity_ = 0.001

end
@mat_prop

prop mat 1 bulk @bulk_modulus g @shear_modulus dens @rock_density bcoh @bcoh_
prop mat 1 bten @bten_ phi @fric_angle psi @dilation_angle
change mat 1 cons 2

;joint material properties for initial stress state, maintain constant aperture

prop jmat 1 jkn @joint_kn jks @joint_ks jfric @j_friction
prop jmat 1 jcoh @j_cohesion jten @j_tension azero @j_ap0 ares @j_ap0 amax @j_ap0

change jmat 1
; assigning fluid properties
fluid bulk @fluid_bulk_ density @fluid_density_ viscosity @fluid_viscosity_

; insitu stress and gradients
def set_insitu
;INPUT
depth = 2950 ; m
gravity_ = 9.81 ; m3/s

KH_max = 0.818 ; ration of maximum horizontal to vertical
Kh_min = 0.788 ; ratio of minimum horizontal to vertical

; Stresses at z= 0 of the model (positive)
szz0 = -rock_density*depth*gravity_ ; Vertical stress as from paper formula -rock_density*depth*gravity_
sxx0 = KH_max*szz0
syy0 = Kh_min*szz0

; fluid pressure at z = 0 (positive)
pp0 = fluid_density_*depth*gravity_ ; if calculated by fluid_density_*depth*gravity_ = 27.5 MPa

;gradients per m in positive z direction

szz_grad = rock_density*gravity_
syy_grad = kh_min*szz_grad
sxx_grad = kH_max*szz_grad
pp_grad = -fluid_density_ * gravity_

end
@set_insitu

;in-situ stress

insitu stress @sxx0 @syy0 @szz0 0. 0. 0. &
      zgrad @sxx_grad @syy_grad @szz_grad 0. 0. 0. nodisp
;insitu pp @pp0 grad 0. 0. @pp_grad nodisp

;Boundary consitions

bound xvel 0.0 yvel 0.0 zvel 0.0 range x 0.825
bound xvel 0.0 yvel 0.0 zvel 0.0 range x -0.825
bound xvel 0.0 yvel 0.0 zvel 0.0 range z 0
bound xvel 0.0 yvel 0.0 zvel 0.0 range z -5
bound xvel 0.0 yvel 0.0 zvel 0.0 range y 0.825
```

```
bound xvel 0.0 yvel 0.0 zvel 0.0 range y -0.825

;bound stress -54e6 0 0 0,0,0 range x 0.825
;bound stress -54e6,0,0 0,0,0 range x -0.825
;bound stress 0 0 -66e6 0,0,0 range z 0
;bound stress 0 0 -66e6 0,0,0 range z -5
;bound stress 0,-52e6,0 0,0,0 range y 0.825
;bound stress 0,-52e6,0 0,0,0 range y -0.825

gravity 0 0 [-gravity_]
set flow off mech on
fluid bulk 0
hist unbal
set small
cyc 200

delete range x -0.075,0.075 y -0.075,0.075 z 0,-5

def reset_aperture
  local fp = flow_head
  loop while fp # 0
    local fpx = fp_fpx(fp)
    loop while fpx # 0
      fpx_apmech(fpx) = j_ap0
      fpx = fpx_next(fpx)
    end_loop
    fp = fp_next(fp)
  end_loop
end

def bh_setup

 ;maximum aperture
 j_ap_max = 30.0e-4
end

@bh_setup
;.....applying pressure in the borehole
bou stress -28e6 -28e6 -28e6 0.0 0.0 0.0 range cylinder end1 0,0,0 end2 0,0,-5 rad 0,0.08


;
; reset displacements, apertures and time
reset disp jdisp
@reset_aperture
set time 0

; change joint materials to allow for joint opening
prop jmat 1 amax @j_ap_max

; flow only occurs through joints that have failed
set crack_flow on

; setup general fluid properties
fluid bulk @fluid_bulk_
fluid volmin 1e-3 areamin 0.25
set flow on mech on

; maximum number of mechanical steps per fluid step
set nmech 5

; inject into center
bound disch 0.053 range x -0.075 0.075 y -0.075 0.075 z 0,-5

; Notes
;the problem is not the whole data file but method of injection
; point 1
```

```
his ndis 0.075 0.075 -2.5
his sdis 0.075 0.075 -2.5
his sstress 0.075 0.075 -2.5
his nstress 0.075 0.075 -2.5
his fluid_pp 0.075 0.075 -2.5
;point 2
his ndis -0.075 0.075 -2.5
his sdis -0.075 0.075 -2.5
his sstress -0.075 0.075 -2.5
his nstress -0.075 0.075 -2.5
his fluid_pp -0.075 0.075 -2.5
;point 3
his ndis -0.075 -0.075 -2.5
his sdis -0.075 -0.075 -2.5
his sstress -0.075 -0.075 -2.5
his nstress -0.075 -0.075 -2.5
his fluid_pp -0.075 -0.075 -2.5
;point 4
his ndis 0.075 -0.075 -2.5
his sdis 0.075 -0.075 -2.5
his sstress 0.075 -0.075 -2.5
his nstress 0.075 -0.075 -2.5
his fluid_pp 0.075 -0.075 -2.5
;point 5
his ndis 0.5 0.5 -2.5
his sdis 0.5 0.5 -2.5
his sstress 0.5 0.5 -2.5
his nstress 0.5 0.5 -2.5
his fluid_pp 0.5 0.5 -2.5
;xdis
his xdis 0.075 0.075 -2.5
his xdis -0.075 0.075 -2.5
his xdis 0.075 -0.075 -2.5
his xdis -0.075 -0.075 -2.5
his time
his unbal


cyc 1500
save HMLP-irwin
```

HPLM Irwin

```
new
config fluid
poly tunnel rad=0.075 leng=0,5 ratr=10.0 dip=90 dd=0 nr=1 nt=1 nx=1

join on
;
jset dip 45 dd 250 spac 0.5 num 30
jset dip 45 dd 180 spac 0.5 num 30

; zoning
gen edge 0.05
def mat_prop

  bulk_modulus = 18.18e9
  Shear_modulus = 9.4e9
  rock_density = 2580
  bcoh_ = 3.55e6
  bten_ = 1e6
  fric_angle = 24
  dilation_angle = 0

  ;Joint properties
```

```
  joint_kn = 9e9
  joint_ks = 6e9
  j_friction = 30
  j_tension = 0.0
  j_cohesion = 0.0
  j_ap0 = 1e-4 ;aperture at 0 normal stress

  ;fluid properties
  fluid_bulk_ = 3e6
  fluid_density_ = 1000.0
  fluid_viscosity_ = 0.001

end
@mat_prop

prop mat 1 bulk @bulk_modulus g @shear_modulus dens @rock_density bcoh @bcoh_
prop mat 1 bten @bten_ phi @fric_angle psi @dilation_angle
change mat 1 cons 2

;joint material properties for initial stress state, maintain constant aperture

prop jmat 1 jkn @joint_kn jks @joint_ks jfric @j_friction
prop jmat 1 jcoh @j_cohesion jten @j_tension azero @j_ap0 ares @j_ap0 amax @j_ap0

change jmat 1
; assigning fluid properties
fluid bulk @fluid_bulk_ density @fluid_density_ viscosity @fluid_viscosity_

; insitu stress and gradients
def set_insitu
;INPUT
depth = 2950 ; m
gravity_ = 9.81 ; m3/s

KH_max = 0.818 ; ration of maximum horizontal to vertical
Kh_min = 0.788 ; ratio of minimum horizontal to vertical

; Stresses at z= 0 of the model (positive)
szz0 = -rock_density*depth*gravity_ ; Vertical stress as from paper formula -rock_density*depth*gravity_
sxx0 = KH_max*szz0
syy0 = Kh_min*szz0

; fluid pressure at z = 0 (positive)
pp0 = fluid_density_*depth*gravity_ ; if calculated by fluid_density_*depth*gravity_ = 27.5 MPa

;gradients per m in positive z direction

szz_grad = rock_density*gravity_
syy_grad = kh_min*szz_grad
sxx_grad = kH_max*szz_grad
pp_grad = -fluid_density_ * gravity_

end
@set_insitu

;in-situ stress

insitu stress @sxx0 @syy0 @szz0 0. 0. 0. &
       zgrad @sxx_grad @syy_grad @szz_grad 0. 0. 0. nodisp
insitu pp @pp0 grad 0. 0. @pp_grad nodisp

;Boundary consitions

bound xvel 0.0 yvel 0.0 zvel 0.0 range x 0.825
bound xvel 0.0 yvel 0.0 zvel 0.0 range x -0.825
bound xvel 0.0 yvel 0.0 zvel 0.0 range z 0
```

```
bound xvel 0.0 yvel 0.0 zvel 0.0 range z -5
bound xvel 0.0 yvel 0.0 zvel 0.0 range y 0.825
bound xvel 0.0 yvel 0.0 zvel 0.0 range y -0.825

;bound stress -54e6 0 0 0,0,0 range x 0.825
;bound stress -54e6,0,0 0,0,0 range x -0.825
;bound stress 0 0 -66e6 0,0,0 range z 0
;bound stress 0 0 -66e6 0,0,0 range z -5
;bound stress 0,-52e6,0 0,0,0 range y 0.825
;bound stress 0,-52e6,0 0,0,0 range y -0.825

gravity 0 0 [-gravity_]
set flow off mech on
fluid bulk 0
hist unbal
set small
cyc 200

delete range x -0.075,0.075 y -0.075,0.075 z 0,-5

def reset_aperture
  local fp = flow_head
  loop while fp # 0
    local fpx = fp_fpx(fp)
    loop while fpx # 0
      fpx_apmech(fpx) = j_ap0
      fpx = fpx_next(fpx)
    end_loop
    fp = fp_next(fp)
  end_loop
end

def bh_setup

 ;maximum aperture
 j_ap_max = 30.0e-4
end

@bh_setup
;.....applying pressure in the borehole
bou stress -28e6 -28e6 -28e6 0.0 0.0 0.0 range cylinder end1 0,0,0 end2 0,0,-5 rad 0,0.08


;
; reset displacements, apertures and time
reset disp jdisp
@reset_aperture
set time 0

; change joint materials to allow for joint opening
prop jmat 1 amax @j_ap_max

; flow only occurs through joints that have failed
set crack_flow on

; setup general fluid properties
fluid bulk @fluid_bulk_
fluid volmin 1e-3 areamin 0.25
set flow on mech on

; maximum number of mechanical steps per fluid step
set nmech 5

; inject into center
;bound disch 0.053 range x -0.075 0.075 y -0.075 0.075 z 0,-5

; Notes
```

```
;the problem is not the whole data file but method of injection
; point 1
his ndis 0.075 0.075 -2.5
his sdis 0.075 0.075 -2.5
his sstress 0.075 0.075 -2.5
his nstress 0.075 0.075 -2.5
his fluid_pp 0.075 0.075 -2.5
;point 2
his ndis -0.075 0.075 -2.5
his sdis -0.075 0.075 -2.5
his sstress -0.075 0.075 -2.5
his nstress -0.075 0.075 -2.5
his fluid_pp -0.075 0.075 -2.5
;point 3
his ndis -0.075 -0.075 -2.5
his sdis -0.075 -0.075 -2.5
his sstress -0.075 -0.075 -2.5
his nstress -0.075 -0.075 -2.5
his fluid_pp -0.075 -0.075 -2.5
;point 4
his ndis 0.075 -0.075 -2.5
his sdis 0.075 -0.075 -2.5
his sstress 0.075 -0.075 -2.5
his nstress 0.075 -0.075 -2.5
his fluid_pp 0.075 -0.075 -2.5
;point 5
his ndis 0.5 0.5 -2.5
his sdis 0.5 0.5 -2.5
his sstress 0.5 0.5 -2.5
his nstress 0.5 0.5 -2.5
his fluid_pp 0.5 0.5 -2.5
;xdis
his xdis 0.075 0.075 -2.5
his xdis -0.075 0.075 -2.5
his xdis 0.075 -0.075 -2.5
his xdis -0.075 -0.075 -2.5
his time
his unbal


cyc 1500
save HPLM-irwin
```

EQMP Irwin

```
new
config fluid
poly tunnel rad=0.075 leng=0,5 ratr=10.0 dip=90 dd=0 nr=1 nt=1 nx=1

join on
;
jset dip 45 dd 250 spac 0.5 num 30
jset dip 45 dd 180 spac 0.5 num 30

; zoning
gen edge 0.05
def mat_prop

  bulk_modulus = 18.18e9
  Shear_modulus = 9.4e9
  rock_density = 2580
  bcoh_ = 3.55e6
  bten_ = 1e6
```

```
  fric_angle = 24
  dilation_angle = 0

  ;Joint properties

  joint_kn = 9e9
  joint_ks = 6e9
  j_friction = 30
  j_tension = 0.0
  j_cohesion = 0.0
  j_ap0 = 1e-4 ;aperture at 0 normal stress

  ;fluid properties
  fluid_bulk_ = 3e6
  fluid_density_ = 1000.0
  fluid_viscosity_ = 0.001

end
@mat_prop

prop mat 1 bulk @bulk_modulus g @shear_modulus dens @rock_density bcoh @bcoh_
prop mat 1 bten @bten_ phi @fric_angle psi @dilation_angle
change mat 1 cons 2

;joint material properties for initial stress state, maintain constant aperture

prop jmat 1 jkn @joint_kn jks @joint_ks jfric @j_friction
prop jmat 1 jcoh @j_cohesion jten @j_tension azero @j_ap0 ares @j_ap0 amax @j_ap0

change jmat 1
; assigning fluid properties
fluid bulk @fluid_bulk_ density @fluid_density_ viscosity @fluid_viscosity_

; insitu stress and gradients
def set_insitu
;INPUT
depth = 2950 ; m
gravity_ = 9.81 ; m3/s

KH_max = 0.818 ; ration of maximum horizontal to vertical
Kh_min = 0.788 ; ratio of minimum horizontal to vertical

; Stresses at z= 0 of the model (positive)
szz0 = -rock_density*depth*gravity_ ; Vertical stress as from paper formula -rock_density*depth*gravity_
sxx0 = KH_max*szz0
syy0 = Kh_min*szz0

; fluid pressure at z = 0 (positive)
pp0 = fluid_density_*depth*gravity_ ; if calculated by fluid_density_*depth*gravity_ = 27.5 MPa

;gradients per m in positive z direction

szz_grad = rock_density*gravity_
syy_grad = kh_min*szz_grad
sxx_grad = kH_max*szz_grad
pp_grad = -fluid_density_ * gravity_

end
@set_insitu

;in-situ stress

insitu stress @sxx0 @syy0 @szz0 0. 0. 0. &
       zgrad @sxx_grad @syy_grad @szz_grad 0. 0. 0. nodisp
insitu pp @pp0 grad 0. 0. @pp_grad nodisp

;Boundary consitions
```

```
bound xvel 0.0 yvel 0.0 zvel 0.0 range x 0.825
bound xvel 0.0 yvel 0.0 zvel 0.0 range x -0.825
bound xvel 0.0 yvel 0.0 zvel 0.0 range z 0
bound xvel 0.0 yvel 0.0 zvel 0.0 range z -5
bound xvel 0.0 yvel 0.0 zvel 0.0 range y 0.825
bound xvel 0.0 yvel 0.0 zvel 0.0 range y -0.825

;bound stress -54e6 0 0 0,0,0 range x 0.825
;bound stress -54e6,0,0 0,0,0 range x -0.825
;bound stress 0 0 -66e6 0,0,0 range z 0
;bound stress 0 0 -66e6 0,0,0 range z -5
;bound stress 0,-52e6,0 0,0,0 range y 0.825
;bound stress 0,-52e6,0 0,0,0 range y -0.825

gravity 0 0 [-gravity_]
set flow off mech on
fluid bulk 0
hist unbal
set small
cyc 200

delete range x -0.075,0.075 y -0.075,0.075 z 0,-5

def reset_aperture
  local fp = flow_head
  loop while fp # 0
    local fpx = fp_fpx(fp)
    loop while fpx # 0
      fpx_apmech(fpx) = j_ap0
      fpx = fpx_next(fpx)
    end_loop
    fp = fp_next(fp)
  end_loop
end

def bh_setup

 ;maximum aperture
 j_ap_max = 30.0e-4
end

@bh_setup
;.....applying pressure in the borehole
bou stress -28e6 -28e6 -28e6 0.0 0.0 0.0 range cylinder end1 0,0,0 end2 0,0,-5 rad 0,0.08


;
; reset displacements, apertures and time
reset disp jdisp
@reset_aperture
set time 0

; change joint materials to allow for joint opening
prop jmat 1 amax @j_ap_max

; flow only occurs through joints that have failed
set crack_flow on

; setup general fluid properties
fluid bulk @fluid_bulk_
fluid volmin 1e-3 areamin 0.25
set flow on mech on

; maximum number of mechanical steps per fluid step
set nmech 5
```

```
; inject into center
bound disch 0.0001 range x -0.075 0.075 y -0.075 0.075 z 0,-5

; Notes
;the problem is not the whole data file but method of injection
; point 1
his ndis 0.075 0.075 -2.5
his sdis 0.075 0.075 -2.5
his sstress 0.075 0.075 -2.5
his nstress 0.075 0.075 -2.5
his fluid_pp 0.075 0.075 -2.5
;point 2
his ndis -0.075 0.075 -2.5
his sdis -0.075 0.075 -2.5
his sstress -0.075 0.075 -2.5
his nstress -0.075 0.075 -2.5
his fluid_pp -0.075 0.075 -2.5
;point 3
his ndis -0.075 -0.075 -2.5
his sdis -0.075 -0.075 -2.5
his sstress -0.075 -0.075 -2.5
his nstress -0.075 -0.075 -2.5
his fluid_pp -0.075 -0.075 -2.5
;point 4
his ndis 0.075 -0.075 -2.5
his sdis 0.075 -0.075 -2.5
his sstress 0.075 -0.075 -2.5
his nstress 0.075 -0.075 -2.5
his fluid_pp 0.075 -0.075 -2.5
;point 5
his ndis 0.5 0.5 -2.5
his sdis 0.5 0.5 -2.5
his sstress 0.5 0.5 -2.5
his nstress 0.5 0.5 -2.5
his fluid_pp 0.5 0.5 -2.5
;xdis
his xdis 0.075 0.075 -2.5
his xdis -0.075 0.075 -2.5
his xdis 0.075 -0.075 -2.5
his xdis -0.075 -0.075 -2.5
his time
his unbal


cyc 1500
save EQMP-irwin

--------------------------------
```

Dry Irwin

```
new
config fluid
poly tunnel rad=0.075 leng=0,5 ratr=10.0 dip=90 dd=0 nr=1 nt=1 nx=1

join on
;
jset dip 45 dd 250 spac 0.5 num 30
jset dip 45 dd 180 spac 0.5 num 30

; zoning
gen edge 0.05
def mat_prop

  bulk_modulus = 18.18e9
  Shear_modulus = 9.4e9
```

```
  rock_density = 2580
  bcoh_ = 3.55e6
  bten_ = 1e6
  fric_angle = 24
  dilation_angle = 0

  ;Joint properties

  joint_kn = 9e9
  joint_ks = 6e9
  j_friction = 30
  j_tension = 0.0
  j_cohesion = 0.0
  j_ap0 = 1e-4 ;aperture at 0 normal stress

  ;fluid properties
  fluid_bulk_ = 3e6
  fluid_density_ = 1000.0
  fluid_viscosity_ = 0.001

end
@mat_prop

prop mat 1 bulk @bulk_modulus g @shear_modulus dens @rock_density bcoh @bcoh_
prop mat 1 bten @bten_ phi @fric_angle psi @dilation_angle
change mat 1 cons 2

;joint material properties for initial stress state, maintain constant aperture

prop jmat 1 jkn @joint_kn jks @joint_ks jfric @j_friction
prop jmat 1 jcoh @j_cohesion jten @j_tension azero @j_ap0 ares @j_ap0 amax @j_ap0

change jmat 1
; assigning fluid properties
fluid bulk @fluid_bulk_ density @fluid_density_ viscosity @fluid_viscosity_

; insitu stress and gradients
def set_insitu
;INPUT
depth = 2950 ; m
gravity_ = 9.81 ; m3/s

KH_max = 0.818 ; ration of maximum horizontal to vertical
Kh_min = 0.788 ; ratio of minimum horizontal to vertical

; Stresses at z= 0 of the model (positive)
szz0 = -rock_density*depth*gravity_ ; Vertical stress as from paper formula -rock_density*depth*gravity_
sxx0 = KH_max*szz0
syy0 = Kh_min*szz0

; fluid pressure at z = 0 (positive)
pp0 = fluid_density_*depth*gravity_ ; if calculated by fluid_density_*depth*gravity_ = 27.5 MPa

;gradients per m in positive z direction

szz_grad = rock_density*gravity_
syy_grad = kh_min*szz_grad
sxx_grad = kH_max*szz_grad
pp_grad = -fluid_density_ * gravity_

end
@set_insitu

;in-situ stress

insitu stress @sxx0 @syy0 @szz0 0. 0. 0. &
      zgrad @sxx_grad @syy_grad @szz_grad 0. 0. 0. nodisp
```

```
;insitu pp @pp0 grad 0. 0. @pp_grad nodisp

;Boundary consitions

bound xvel 0.0 yvel 0.0 zvel 0.0 range x 0.825
bound xvel 0.0 yvel 0.0 zvel 0.0 range x -0.825
bound xvel 0.0 yvel 0.0 zvel 0.0 range z 0
bound xvel 0.0 yvel 0.0 zvel 0.0 range z -5
bound xvel 0.0 yvel 0.0 zvel 0.0 range y 0.825
bound xvel 0.0 yvel 0.0 zvel 0.0 range y -0.825

;bound stress -54e6 0 0 0,0,0 range x 0.825
;bound stress -54e6,0,0 0,0,0 range x -0.825
;bound stress 0 0 -66e6 0,0,0 range z 0
;bound stress 0 0 -66e6 0,0,0 range z -5
;bound stress 0,-52e6,0 0,0,0 range y 0.825
;bound stress 0,-52e6,0 0,0,0 range y -0.825

gravity 0 0 [-gravity_]
set flow off mech on
fluid bulk 0
hist unbal
set small
cyc 200

delete range x -0.075,0.075 y -0.075,0.075 z 0,-5

def reset_aperture
  local fp = flow_head
  loop while fp # 0
    local fpx = fp_fpx(fp)
    loop while fpx # 0
      fpx_apmech(fpx) = j_ap0
      fpx = fpx_next(fpx)
    end_loop
    fp = fp_next(fp)
  end_loop
end

def bh_setup

 ;maximum aperture
 j_ap_max = 30.0e-4
end

@bh_setup
;.....applying pressure in the borehole
bou stress -28e6 -28e6 -28e6 0.0 0.0 0.0 range cylinder end1 0,0,0 end2 0,0,-5 rad 0,0.08


;
; reset displacements, apertures and time
reset disp jdisp
@reset_aperture
set time 0

; change joint materials to allow for joint opening
prop jmat 1 amax @j_ap_max

; flow only occurs through joints that have failed
set crack_flow on

; setup general fluid properties
fluid bulk @fluid_bulk_
fluid volmin 1e-3 areamin 0.25
set flow on mech on
```

```
; maximum number of mechanical steps per fluid step
set nmech 5

; inject into center
;bound disch 0.053 range x -0.075 0.075 y -0.075 0.075 z 0,-5

; Notes
;the problem is not the whole data file but method of injection
; point 1
his ndis 0.075 0.075 -2.5
his sdis 0.075 0.075 -2.5
his sstress 0.075 0.075 -2.5
his nstress 0.075 0.075 -2.5
his fluid_pp 0.075 0.075 -2.5
;point 2
his ndis -0.075 0.075 -2.5
his sdis -0.075 0.075 -2.5
his sstress -0.075 0.075 -2.5
his nstress -0.075 0.075 -2.5
his fluid_pp -0.075 0.075 -2.5
;point 3
his ndis -0.075 -0.075 -2.5
his sdis -0.075 -0.075 -2.5
his sstress -0.075 -0.075 -2.5
his nstress -0.075 -0.075 -2.5
his fluid_pp -0.075 -0.075 -2.5
;point 4
his ndis 0.075 -0.075 -2.5
his sdis 0.075 -0.075 -2.5
his sstress 0.075 -0.075 -2.5
his nstress 0.075 -0.075 -2.5
his fluid_pp 0.075 -0.075 -2.5
;point 5
his ndis 0.5 0.5 -2.5
his sdis 0.5 0.5 -2.5
his sstress 0.5 0.5 -2.5
his nstress 0.5 0.5 -2.5
his fluid_pp 0.5 0.5 -2.5
;xdis
his xdis 0.075 0.075 -2.5
his xdis -0.075 0.075 -2.5
his xdis 0.075 -0.075 -2.5
his xdis -0.075 -0.075 -2.5
his time
his unbal


cyc 1500
save dry-irwin
```

Kockatea Shale

HPLM Kockatea

```
new
config fluid
poly tunnel rad=0.075 leng=0,5 ratr=10.0 dip=90 dd=0 nr=1 nt=1 nx=1

join on
;
jset dip 45 dd 250 spac 0.5 num 30
jset dip 45 dd 180 spac 0.5 num 30
```

```
; zoning
gen edge 0.05
def mat_prop

  bulk_modulus = 14.16e9
  Shear_modulus = 6.53e9
  rock_density = 2650
  bcoh_ = 0.55e6
  bten_ = 5.3e6
  fric_angle = 24
  dilation_angle = 0

  ;Joint properties

  joint_kn = 9e9
  joint_ks = 6e9
  j_friction = 30
  j_tension = 0.0
  j_cohesion = 0.0
  j_ap0 = 1e-4 ;aperture at 0 normal stress

  ;fluid properties
  fluid_bulk_ = 3e6
  fluid_density_ = 1000.0
  fluid_viscosity_ = 0.001

end
@mat_prop

prop mat 1 bulk @bulk_modulus g @shear_modulus dens @rock_density bcoh @bcoh_
prop mat 1 bten @bten_ phi @fric_angle psi @dilation_angle
change mat 1 cons 2

;joint material properties for initial stress state, maintain constant aperture

prop jmat 1 jkn @joint_kn jks @joint_ks jfric @j_friction
prop jmat 1 jcoh @j_cohesion jten @j_tension azero @j_ap0 ares @j_ap0 amax @j_ap0

change jmat 1
; assigning fluid properties
fluid bulk @fluid_bulk_ density @fluid_density_ viscosity @fluid_viscosity_

; insitu stress and gradients
def set_insitu
;INPUT
depth = 2500 ; m
gravity_ = 9.81 ; m3/s

KH_max = 0.818 ; ration of maximum horizontal to vertical
Kh_min = 0.788 ; ratio of minimum horizontal to vertical

; Stresses at z= 0 of the model (positive)
szz0 = -rock_density*depth*gravity_ ; Vertical stress as from paper formula -rock_density*depth*gravity_
sxx0 = KH_max*szz0
syy0 = Kh_min*szz0

; fluid pressure at z = 0 (positive)
pp0 = fluid_density_*depth*gravity_ ; if calculated by fluid_density_*depth*gravity_ = 27.5 MPa

;gradients per m in positive z direction

szz_grad = rock_density*gravity_
syy_grad = kh_min*szz_grad
sxx_grad = kH_max*szz_grad
pp_grad = -fluid_density_ * gravity_

end
```

```
@set_insitu

;in-situ stress

insitu stress @sxx0 @syy0 @szz0 0. 0. 0. &
       zgrad @sxx_grad @syy_grad @szz_grad 0. 0. 0. nodisp
insitu pp @pp0 grad 0. 0. @pp_grad nodisp

;Boundary consitions

bound xvel 0.0 yvel 0.0 zvel 0.0 range x 0.825
bound xvel 0.0 yvel 0.0 zvel 0.0 range x -0.825
bound xvel 0.0 yvel 0.0 zvel 0.0 range z 0
bound xvel 0.0 yvel 0.0 zvel 0.0 range z -5
bound xvel 0.0 yvel 0.0 zvel 0.0 range y 0.825
bound xvel 0.0 yvel 0.0 zvel 0.0 range y -0.825

;bound stress -54e6 0 0 0,0,0 range x 0.825
;bound stress -54e6,0,0 0,0,0 range x -0.825
;bound stress 0 0 -66e6 0,0,0 range z 0
;bound stress 0 0 -66e6 0,0,0 range z -5
;bound stress 0,-52e6,0 0,0,0 range y 0.825
;bound stress 0,-52e6,0 0,0,0 range y -0.825

gravity 0 0 [-gravity_]
set flow off mech on
fluid bulk 0
hist unbal
set small
cyc 200

delete range x -0.075,0.075 y -0.075,0.075 z 0,-5

def reset_aperture
  local fp = flow_head
  loop while fp # 0
    local fpx = fp_fpx(fp)
    loop while fpx # 0
      fpx_apmech(fpx) = j_ap0
      fpx = fpx_next(fpx)
    end_loop
    fp = fp_next(fp)
  end_loop
end

def bh_setup

 ;maximum aperture
 j_ap_max = 30.0e-4
end

@bh_setup
;.....applying pressure in the borehole
bou stress -28e6 -28e6 -28e6 0.0 0.0 0.0 range cylinder end1 0,0,0 end2 0,0,-5 rad 0,0.08


;
; reset displacements, apertures and time
reset disp jdisp
@reset_aperture
set time 0

; change joint materials to allow for joint opening
prop jmat 1 amax @j_ap_max

; flow only occurs through joints that have failed
set crack_flow on
```

```
; setup general fluid properties
fluid bulk @fluid_bulk_
fluid volmin 1e-3 areamin 0.25
set flow on mech on

; maximum number of mechanical steps per fluid step
set nmech 5

; inject into center
;bound disch 0.053 range x -0.075 0.075 y -0.075 0.075 z 0,-5

; Notes
;the problem is not the whole data file but method of injection
; point 1
his ndis 0.075 0.075 -2.5
his sdis 0.075 0.075 -2.5
his sstress 0.075 0.075 -2.5
his nstress 0.075 0.075 -2.5
his fluid_pp 0.075 0.075 -2.5
;point 2
his ndis -0.075 0.075 -2.5
his sdis -0.075 0.075 -2.5
his sstress -0.075 0.075 -2.5
his nstress -0.075 0.075 -2.5
his fluid_pp -0.075 0.075 -2.5
;point 3
his ndis -0.075 -0.075 -2.5
his sdis -0.075 -0.075 -2.5
his sstress -0.075 -0.075 -2.5
his nstress -0.075 -0.075 -2.5
his fluid_pp -0.075 -0.075 -2.5
;point 4
his ndis 0.075 -0.075 -2.5
his sdis 0.075 -0.075 -2.5
his sstress 0.075 -0.075 -2.5
his nstress 0.075 -0.075 -2.5
his fluid_pp 0.075 -0.075 -2.5
;point 5
his ndis 0.5 0.5 -2.5
his sdis 0.5 0.5 -2.5
his sstress 0.5 0.5 -2.5
his nstress 0.5 0.5 -2.5
his fluid_pp 0.5 0.5 -2.5
;xdis
his xdis 0.075 0.075 -2.5
his xdis -0.075 0.075 -2.5
his xdis 0.075 -0.075 -2.5
his xdis -0.075 -0.075 -2.5
his time
his unbal


cyc 1500
save HMLP-Kockatea
```

HMLP Kockatea

```
new
config fluid
poly tunnel rad=0.075 leng=0,5 ratr=10.0 dip=90 dd=0 nr=1 nt=1 nx=1

join on
;
jset dip 45 dd 250 spac 0.5 num 30
```

```
jset dip 45 dd 180 spac 0.5 num 30

; zoning
gen edge 0.05
def mat_prop

  bulk_modulus = 14.16e9
  Shear_modulus = 6.53e9
  rock_density = 2650
  bcoh_ = 0.55e6
  bten_ = 5.3e6
  fric_angle = 24
  dilation_angle = 0

  ;Joint properties

  joint_kn = 9e9
  joint_ks = 6e9
  j_friction = 30
  j_tension = 0.0
  j_cohesion = 0.0
  j_ap0 = 1e-4 ;aperture at 0 normal stress

  ;fluid properties
  fluid_bulk_ = 3e6
  fluid_density_ = 1000.0
  fluid_viscosity_ = 0.001

end
@mat_prop

prop mat 1 bulk @bulk_modulus g @shear_modulus dens @rock_density bcoh @bcoh_
prop mat 1 bten @bten_ phi @fric_angle psi @dilation_angle
change mat 1 cons 2

;joint material properties for initial stress state, maintain constant aperture

prop jmat 1 jkn @joint_kn jks @joint_ks jfric @j_friction
prop jmat 1 jcoh @j_cohesion jten @j_tension azero @j_ap0 ares @j_ap0 amax @j_ap0

change jmat 1
; assigning fluid properties
fluid bulk @fluid_bulk_ density @fluid_density_ viscosity @fluid_viscosity_

; insitu stress and gradients
def set_insitu
;INPUT
depth = 2500 ; m
gravity_ = 9.81 ; m3/s

KH_max = 0.818 ; ration of maximum horizontal to vertical
Kh_min = 0.788 ; ratio of minimum horizontal to vertical

; Stresses at z= 0 of the model (positive)
szz0 = -rock_density*depth*gravity_ ; Vertical stress as from paper formula -rock_density*depth*gravity_
sxx0 = KH_max*szz0
syy0 = Kh_min*szz0

; fluid pressure at z = 0 (positive)
pp0 = fluid_density_*depth*gravity_ ; if calculated by fluid_density_*depth*gravity_ = 27.5 MPa

;gradients per m in positive z direction

szz_grad = rock_density*gravity_
syy_grad = kh_min*szz_grad
sxx_grad = kH_max*szz_grad
pp_grad = -fluid_density_ * gravity_
```

```
end
@set_insitu

;in-situ stress

insitu stress @sxx0 @syy0 @szz0 0. 0. 0. &
       zgrad @sxx_grad @syy_grad @szz_grad 0. 0. 0. nodisp
;insitu pp @pp0 grad 0. 0. @pp_grad nodisp

;Boundary consitions

bound xvel 0.0 yvel 0.0 zvel 0.0 range x 0.825
bound xvel 0.0 yvel 0.0 zvel 0.0 range x -0.825
bound xvel 0.0 yvel 0.0 zvel 0.0 range z 0
bound xvel 0.0 yvel 0.0 zvel 0.0 range z -5
bound xvel 0.0 yvel 0.0 zvel 0.0 range y 0.825
bound xvel 0.0 yvel 0.0 zvel 0.0 range y -0.825

;bound stress -54e6 0 0 0,0,0 range x 0.825
;bound stress -54e6,0,0 0,0,0 range x -0.825
;bound stress 0 0 -66e6 0,0,0 range z 0
;bound stress 0 0 -66e6 0,0,0 range z -5
;bound stress 0,-52e6,0 0,0,0 range y 0.825
;bound stress 0,-52e6,0 0,0,0 range y -0.825

gravity 0 0 [-gravity_]
set flow off mech on
fluid bulk 0
hist unbal
set small
cyc 200

delete range x -0.075,0.075 y -0.075,0.075 z 0,-5

def reset_aperture
  local fp = flow_head
  loop while fp # 0
    local fpx = fp_fpx(fp)
    loop while fpx # 0
      fpx_apmech(fpx) = j_ap0
      fpx = fpx_next(fpx)
    end_loop
    fp = fp_next(fp)
  end_loop
end

def bh_setup

 ;maximum aperture
 j_ap_max = 30.0e-4
end

@bh_setup
;.....applying pressure in the borehole
bou stress -28e6 -28e6 -28e6 0.0 0.0 0.0 range cylinder end1 0,0,0 end2 0,0,-5 rad 0,0.08


;
; reset displacements, apertures and time
reset disp jdisp
@reset_aperture
set time 0

; change joint materials to allow for joint opening
prop jmat 1 amax @j_ap_max
```

```
; flow only occurs through joints that have failed
set crack_flow on

; setup general fluid properties
fluid bulk @fluid_bulk_
fluid volmin 1e-3 areamin 0.25
set flow on mech on

; maximum number of mechanical steps per fluid step
set nmech 5

; inject into center
bound disch 0.053 range x -0.075 0.075 y -0.075 0.075 z 0,-5

; Notes
;the problem is not the whole data file but method of injection
; point 1
his ndis 0.075 0.075 -2.5
his sdis 0.075 0.075 -2.5
his sstress 0.075 0.075 -2.5
his nstress 0.075 0.075 -2.5
his fluid_pp 0.075 0.075 -2.5
;point 2
his ndis -0.075 0.075 -2.5
his sdis -0.075 0.075 -2.5
his sstress -0.075 0.075 -2.5
his nstress -0.075 0.075 -2.5
his fluid_pp -0.075 0.075 -2.5
;point 3
his ndis -0.075 -0.075 -2.5
his sdis -0.075 -0.075 -2.5
his sstress -0.075 -0.075 -2.5
his nstress -0.075 -0.075 -2.5
his fluid_pp -0.075 -0.075 -2.5
;point 4
his ndis 0.075 -0.075 -2.5
his sdis 0.075 -0.075 -2.5
his sstress 0.075 -0.075 -2.5
his nstress 0.075 -0.075 -2.5
his fluid_pp 0.075 -0.075 -2.5
;point 5
his ndis 0.5 0.5 -2.5
his sdis 0.5 0.5 -2.5
his sstress 0.5 0.5 -2.5
his nstress 0.5 0.5 -2.5
his fluid_pp 0.5 0.5 -2.5
;xdis
his xdis 0.075 0.075 -2.5
his xdis -0.075 0.075 -2.5
his xdis 0.075 -0.075 -2.5
his xdis -0.075 -0.075 -2.5
his time
his unbal


cyc 1500
save HMLp-Kockatea-real
```

EQMP Kockatea

```
new
config fluid
poly tunnel rad=0.075 leng=0,5 ratr=10.0 dip=90 dd=0 nr=1 nt=1 nx=1
```

```
join on
;
jset dip 45 dd 250 spac 0.5 num 30
jset dip 45 dd 180 spac 0.5 num 30

; zoning
gen edge 0.05
def mat_prop

  bulk_modulus = 14.16e9
  Shear_modulus = 6.53e9
  rock_density = 2650
  bcoh_ = 0.55e6
  bten_ = 5.3e6
  fric_angle = 24
  dilation_angle = 0

  ;Joint properties

  joint_kn = 9e9
  joint_ks = 6e9
  j_friction = 30
  j_tension = 0.0
  j_cohesion = 0.0
  j_ap0 = 1e-4 ;aperture at 0 normal stress

  ;fluid properties
  fluid_bulk_ = 3e6
  fluid_density_ = 1000.0
  fluid_viscosity_ = 0.001

end
@mat_prop

prop mat 1 bulk @bulk_modulus g @shear_modulus dens @rock_density bcoh @bcoh_
prop mat 1 bten @bten_ phi @fric_angle psi @dilation_angle
change mat 1 cons 2

;joint material properties for initial stress state, maintain constant aperture

prop jmat 1 jkn @joint_kn jks @joint_ks jfric @j_friction
prop jmat 1 jcoh @j_cohesion jten @j_tension azero @j_ap0 ares @j_ap0 amax @j_ap0

change jmat 1
; assigning fluid properties
fluid bulk @fluid_bulk_ density @fluid_density_ viscosity @fluid_viscosity_

; insitu stress and gradients
def set_insitu
;INPUT
depth = 2500 ; m
gravity_ = 9.81 ; m3/s

KH_max = 0.818 ; ration of maximum horizontal to vertical
Kh_min = 0.788 ; ratio of minimum horizontal to vertical

; Stresses at z= 0 of the model (positive)
szz0 = -rock_density*depth*gravity_ ; Vertical stress as from paper formula -rock_density*depth*gravity_
sxx0 = KH_max*szz0
syy0 = Kh_min*szz0

; fluid pressure at z = 0 (positive)
pp0 = fluid_density_*depth*gravity_ ; if calculated by fluid_density_*depth*gravity_ = 27.5 MPa

;gradients per m in positive z direction

szz_grad = rock_density*gravity_
```

```
syy_grad = kh_min*szz_grad
sxx_grad = kH_max*szz_grad
pp_grad = -fluid_density_ * gravity_

end
@set_insitu

;in-situ stress

insitu stress @sxx0 @syy0 @szz0 0. 0. 0. &
       zgrad @sxx_grad @syy_grad @szz_grad 0. 0. 0. nodisp
insitu pp @pp0 grad 0. 0. @pp_grad nodisp

;Boundary consitions

bound xvel 0.0 yvel 0.0 zvel 0.0 range x 0.825
bound xvel 0.0 yvel 0.0 zvel 0.0 range x -0.825
bound xvel 0.0 yvel 0.0 zvel 0.0 range z 0
bound xvel 0.0 yvel 0.0 zvel 0.0 range z -5
bound xvel 0.0 yvel 0.0 zvel 0.0 range y 0.825
bound xvel 0.0 yvel 0.0 zvel 0.0 range y -0.825

;bound stress -54e6 0 0 0,0,0 range x 0.825
;bound stress -54e6,0,0 0,0,0 range x -0.825
;bound stress 0 0 -66e6 0,0,0 range z 0
;bound stress 0 0 -66e6 0,0,0 range z -5
;bound stress 0,-52e6,0 0,0,0 range y 0.825
;bound stress 0,-52e6,0 0,0,0 range y -0.825

gravity 0 0 [-gravity_]
set flow off mech on
fluid bulk 0
hist unbal
set small
cyc 200

delete range x -0.075,0.075 y -0.075,0.075 z 0,-5

def reset_aperture
  local fp = flow_head
  loop while fp # 0
    local fpx = fp_fpx(fp)
    loop while fpx # 0
      fpx_apmech(fpx) = j_ap0
      fpx = fpx_next(fpx)
    end_loop
    fp = fp_next(fp)
  end_loop
end

def bh_setup

 ;maximum aperture
 j_ap_max = 30.0e-4
end

@bh_setup
;.....applying pressure in the borehole
bou stress -28e6 -28e6 -28e6 0.0 0.0 0.0 range cylinder end1 0,0,0 end2 0,0,-5 rad 0,0.08


;
; reset displacements, apertures and time
reset disp jdisp
@reset_aperture
set time 0
```

```
; change joint materials to allow for joint opening
prop jmat 1 amax @j_ap_max

; flow only occurs through joints that have failed
set crack_flow on

; setup general fluid properties
fluid bulk @fluid_bulk_
fluid volmin 1e-3 areamin 0.25
set flow on mech on

; maximum number of mechanical steps per fluid step
set nmech 5

; inject into center
bound disch 0.0001 range x -0.075 0.075 y -0.075 0.075 z 0,-5

; Notes
;the problem is not the whole data file but method of injection
; point 1
his ndis 0.075 0.075 -2.5
his sdis 0.075 0.075 -2.5
his sstress 0.075 0.075 -2.5
his nstress 0.075 0.075 -2.5
his fluid_pp 0.075 0.075 -2.5
;point 2
his ndis -0.075 0.075 -2.5
his sdis -0.075 0.075 -2.5
his sstress -0.075 0.075 -2.5
his nstress -0.075 0.075 -2.5
his fluid_pp -0.075 0.075 -2.5
;point 3
his ndis -0.075 -0.075 -2.5
his sdis -0.075 -0.075 -2.5
his sstress -0.075 -0.075 -2.5
his nstress -0.075 -0.075 -2.5
his fluid_pp -0.075 -0.075 -2.5
;point 4
his ndis 0.075 -0.075 -2.5
his sdis 0.075 -0.075 -2.5
his sstress 0.075 -0.075 -2.5
his nstress 0.075 -0.075 -2.5
his fluid_pp 0.075 -0.075 -2.5
;point 5
his ndis 0.5 0.5 -2.5
his sdis 0.5 0.5 -2.5
his sstress 0.5 0.5 -2.5
his nstress 0.5 0.5 -2.5
his fluid_pp 0.5 0.5 -2.5
;xdis
his xdis 0.075 0.075 -2.5
his xdis -0.075 0.075 -2.5
his xdis 0.075 -0.075 -2.5
his xdis -0.075 -0.075 -2.5
his time
his unbal


cyc 1500
save EQMP-Kockatea
```

Dryhole Kockatea Shale

```
new
config fluid
```

```
poly tunnel rad=0.075 leng=0,5 ratr=10.0 dip=90 dd=0 nr=1 nt=1 nx=1

join on
;
jset dip 45 dd 250 spac 0.5 num 30
jset dip 45 dd 180 spac 0.5 num 30

; zoning
gen edge 0.05
def mat_prop

  bulk_modulus = 14.16e9
  Shear_modulus = 6.53e9
  rock_density = 2650
  bcoh_ = 0.55e6
  bten_ = 5.3e6
  fric_angle = 24
  dilation_angle = 0

  ;Joint properties

  joint_kn = 9e9
  joint_ks = 6e9
  j_friction = 30
  j_tension = 0.0
  j_cohesion = 0.0
  j_ap0 = 1e-4 ;aperture at 0 normal stress

  ;fluid properties
  fluid_bulk_ = 3e6
  fluid_density_ = 1000.0
  fluid_viscosity_ = 0.001

end
@mat_prop

prop mat 1 bulk @bulk_modulus g @shear_modulus dens @rock_density bcoh @bcoh_
prop mat 1 bten @bten_ phi @fric_angle psi @dilation_angle
change mat 1 cons 2

;joint material properties for initial stress state, maintain constant aperture

prop jmat 1 jkn @joint_kn jks @joint_ks jfric @j_friction
prop jmat 1 jcoh @j_cohesion jten @j_tension azero @j_ap0 ares @j_ap0 amax @j_ap0

change jmat 1
; assigning fluid properties
fluid bulk @fluid_bulk_ density @fluid_density_ viscosity @fluid_viscosity_

; insitu stress and gradients
def set_insitu
;INPUT
depth = 2500 ; m
gravity_ = 9.81 ; m3/s

KH_max = 0.818 ; ration of maximum horizontal to vertical
Kh_min = 0.788 ; ratio of minimum horizontal to vertical

; Stresses at z= 0 of the model (positive)
szz0 = -rock_density*depth*gravity_ ; Vertical stress as from paper formula -rock_density*depth*gravity_
sxx0 = KH_max*szz0
syy0 = Kh_min*szz0

; fluid pressure at z = 0 (positive)
pp0 = fluid_density_*depth*gravity_ ; if calculated by fluid_density_*depth*gravity_ = 27.5 MPa

;gradients per m in positive z direction
```

```
szz_grad = rock_density*gravity_
syy_grad = kh_min*szz_grad
sxx_grad = kH_max*szz_grad
pp_grad = -fluid_density_ * gravity_

end
@set_insitu

;in-situ stress

insitu stress @sxx0 @syy0 @szz0 0. 0. 0. &
       zgrad @sxx_grad @syy_grad @szz_grad 0. 0. 0. nodisp
;insitu pp @pp0 grad 0. 0. @pp_grad nodisp

;Boundary consitions

bound xvel 0.0 yvel 0.0 zvel 0.0 range x 0.825
bound xvel 0.0 yvel 0.0 zvel 0.0 range x -0.825
bound xvel 0.0 yvel 0.0 zvel 0.0 range z 0
bound xvel 0.0 yvel 0.0 zvel 0.0 range z -5
bound xvel 0.0 yvel 0.0 zvel 0.0 range y 0.825
bound xvel 0.0 yvel 0.0 zvel 0.0 range y -0.825

;bound stress -54e6 0 0 0,0,0 range x 0.825
;bound stress -54e6,0,0 0,0,0 range x -0.825
;bound stress 0 0 -66e6 0,0,0 range z 0
;bound stress 0 0 -66e6 0,0,0 range z -5
;bound stress 0,-52e6,0 0,0,0 range y 0.825
;bound stress 0,-52e6,0 0,0,0 range y -0.825

gravity 0 0 [-gravity_]
set flow off mech on
fluid bulk 0
hist unbal
set small
cyc 200

delete range x -0.075,0.075 y -0.075,0.075 z 0,-5

def reset_aperture
  local fp = flow_head
  loop while fp # 0
    local fpx = fp_fpx(fp)
    loop while fpx # 0
      fpx_apmech(fpx) = j_ap0
      fpx = fpx_next(fpx)
    end_loop
    fp = fp_next(fp)
  end_loop
end

def bh_setup

 ;maximum aperture
 j_ap_max = 30.0e-4
end

@bh_setup
;.....applying pressure in the borehole
bou stress -28e6 -28e6 -28e6 0.0 0.0 0.0 range cylinder end1 0,0,0 end2 0,0,-5 rad 0,0.08


;
; reset displacements, apertures and time
reset disp jdisp
@reset_aperture
```

```
set time 0

; change joint materials to allow for joint opening
prop jmat 1 amax @j_ap_max

; flow only occurs through joints that have failed
set crack_flow on

; setup general fluid properties
fluid bulk @fluid_bulk_
fluid volmin 1e-3 areamin 0.25
set flow on mech on

; maximum number of mechanical steps per fluid step
set nmech 5

; inject into center
;bound disch 0.053 range x -0.075 0.075 y -0.075 0.075 z 0,-5

; Notes
;the problem is not the whole data file but method of injection
; point 1
his ndis 0.075 0.075 -2.5
his sdis 0.075 0.075 -2.5
his sstress 0.075 0.075 -2.5
his nstress 0.075 0.075 -2.5
his fluid_pp 0.075 0.075 -2.5
;point 2
his ndis -0.075 0.075 -2.5
his sdis -0.075 0.075 -2.5
his sstress -0.075 0.075 -2.5
his nstress -0.075 0.075 -2.5
his fluid_pp -0.075 0.075 -2.5
;point 3
his ndis -0.075 -0.075 -2.5
his sdis -0.075 -0.075 -2.5
his sstress -0.075 -0.075 -2.5
his nstress -0.075 -0.075 -2.5
his fluid_pp -0.075 -0.075 -2.5
;point 4
his ndis 0.075 -0.075 -2.5
his sdis 0.075 -0.075 -2.5
his sstress 0.075 -0.075 -2.5
his nstress 0.075 -0.075 -2.5
his fluid_pp 0.075 -0.075 -2.5
;point 5
his ndis 0.5 0.5 -2.5
his sdis 0.5 0.5 -2.5
his sstress 0.5 0.5 -2.5
his nstress 0.5 0.5 -2.5
his fluid_pp 0.5 0.5 -2.5
;xdis
his xdis 0.075 0.075 -2.5
his xdis -0.075 0.075 -2.5
his xdis 0.075 -0.075 -2.5
his xdis -0.075 -0.075 -2.5
his time
his unbal


cyc 1500
save dry-kockatea

-------------------------
```

Parametric study

BPM

20 BPM

```
new
config fluid
set atol 0.002
poly tunnel rad=0.1 leng=0,5 ratr=10.0 dip=90 dd=0 nr=1 nt=1 nx=1

join on
;
jset dip 45 dd 250 spac 0.5 num 30
jset dip 45 dd 180 spac 0.5 num 30

; zoning
gen edge 0.05
def mat_prop

  bulk_modulus = 20.90e9
  Shear_modulus = 10.78e9
  rock_density = 2600
  bcoh_ = 6e6
  bten_ = 8e6
  fric_angle = 28
  dilation_angle = 0

  ;Joint properties

  joint_kn = 9e9
  joint_ks = 6e9
  j_friction = 30
  j_tension = 0.0
  j_cohesion = 0.0
  j_ap0 = 1e-4 ;aperture at 0 normal stress

  ;fluid properties
  fluid_bulk_ = 3e6
  fluid_density_ = 1000.0
  fluid_viscosity_ = 0.001

end
@mat_prop

prop mat 1 bulk @bulk_modulus g @shear_modulus dens @rock_density bcoh @bcoh_
prop mat 1 bten @bten_ phi @fric_angle psi @dilation_angle
change mat 1 cons 2

;joint material properties for initial stress state, maintain constant aperture

prop jmat 1 jkn @joint_kn jks @joint_ks jfric @j_friction
prop jmat 1 jcoh @j_cohesion jten @j_tension azero @j_ap0 ares @j_ap0 amax @j_ap0

change jmat 1
; assigning fluid properties
fluid bulk @fluid_bulk_ density @fluid_density_ viscosity @fluid_viscosity_

; insitu stress and gradients
def set_insitu
;INPUT
depth = 2780 ; m
gravity_ = 9.81 ; m3/s

KH_max = 0.818 ; ration of maximum horizontal to vertical
Kh_min = 0.788 ; ratio of minimum horizontal to vertical

; Stresses at z= 0 of the model (positive)
```

```
szz0 = -rock_density*depth*gravity_ ; Vertical stress as from paper formula -rock_density*depth*gravity_
sxx0 = KH_max*szz0
syy0 = Kh_min*szz0

; fluid pressure at z = 0 (positive)
pp0 = fluid_density_*depth*gravity_ ; if calculated by fluid_density_*depth*gravity_ = 27.5 MPa

;gradients per m in positive z direction

szz_grad = rock_density*gravity_
syy_grad = kh_min*szz_grad
sxx_grad = kH_max*szz_grad
pp_grad = -fluid_density_ * gravity_

end
@set_insitu

;in-situ stress

insitu stress @sxx0 @syy0 @szz0 0. 0. 0. &
      zgrad @sxx_grad @syy_grad @szz_grad 0. 0. 0. nodisp
insitu pp @pp0 grad 0. 0. @pp_grad nodisp

;Boundary consitions

;bound xvel 0.0 yvel 0.0 zvel 0.0 range x 0.825
;bound xvel 0.0 yvel 0.0 zvel 0.0 range x -0.825
bound xvel 0.0 yvel 0.0 zvel 0.0 range z 0
bound xvel 0.0 yvel 0.0 zvel 0.0 range z -5
;bound xvel 0.0 yvel 0.0 zvel 0.0 range y 0.825
;bound xvel 0.0 yvel 0.0 zvel 0.0 range y -0.825

;bound stress -54e6 0 0 0,0,0 range x 0.825
;bound stress -54e6,0,0 0,0,0 range x -0.825
;bound stress 0 0 -66e6 0,0,0 range z 0
;bound stress 0 0 -66e6 0,0,0 range z -5
;bound stress 0,-52e6,0 0,0,0 range y 0.825
;bound stress 0,-52e6,0 0,0,0 range y -0.825

gravity 0 0 [-gravity_]
set flow off mech on
fluid bulk 0
hist unbal
set small
cyc 200

delete range cylinder end1 0.1 0.1 0.0 end2 0.1 0.1 -5.0 rad 0, 0.1

def reset_aperture
  local fp = flow_head
  loop while fp # 0
    local fpx = fp_fpx(fp)
    loop while fpx # 0
      fpx_apmech(fpx) = j_ap0
      fpx = fpx_next(fpx)
    end_loop
    fp = fp_next(fp)
  end_loop
end

def bh_setup

 ;maximum aperture
 j_ap_max = 30.0e-4
end

@bh_setup
```

```
;.....applying pressure in the borehole
;bou stress -28e6 -28e6 -28e6 0.0 0.0 0.0 range cylinder end1 0,0,0 end2 0,0,-5 rad 0,0.075


;
; reset displacements, apertures and time
reset disp jdisp
@reset_aperture
set time 0

; change joint materials to allow for joint opening
prop jmat 1 amax @j_ap_max

; flow only occurs through joints that have failed
set crack_flow on

; setup general fluid properties
fluid bulk @fluid_bulk_
fluid volmin 1e-3 areamin 0.25
set flow on mech on

; maximum number of mechanical steps per fluid step
set nmech 5

; inject into center
bound disch 0.053 range cyl end1 0 0 0 end2 0 0 -5 rad 0.0,0.1

; Notes
;the problem is not the whole data file but method of injection
; point 1
his ndis 0.1 0.1 -2.5
his sdis 0.1 0.1 -2.5
his sstress 0.1 0.1 -2.5
his nstress 0.1 0.1 -2.5
his fluid_pp 0.1 0.1 -2.5
;point 2
his ndis -0.1 0.1 -2.5
his sdis -0.1 0.1 -2.5
his sstress -0.1 0.1 -2.5
his nstress -0.1 0.1 -2.5
his fluid_pp -0.1 0.1 -2.5
;point 3
his ndis -0.1 -0.1 -2.5
his sdis -0.1 -0.1 -2.5
his sstress -0.1 -0.1 -2.5
his nstress -0.1 -0.1 -2.5
his fluid_pp -0.1 -0.1 -2.5
;point 4
his ndis 0.1 -0.1 -2.5
his sdis 0.1 -0.1 -2.5
his sstress 0.1 -0.1 -2.5
his nstress 0.1 -0.1 -2.5
his fluid_pp 0.1 -0.1 -2.5
;point 5
his ndis 0.5 0.5 -2.5
his sdis 0.5 0.5 -2.5
his sstress 0.5 0.5 -2.5
his nstress 0.5 0.5 -2.5
his fluid_pp 0.5 0.5 -2.5
;xdis
his xdis 0.1 0.1 -2.5
his xdis -0.1 0.1 -2.5
his xdis 0.1 -0.1 -2.5
his xdis -0.1 -0.1 -2.5
his time
his unbal
```

```
cyc 500
save 20-BPM
------------------------------------
```

40 BPM

```
new
config fluid
set atol 0.002
poly tunnel rad=0.1 leng=0,5 ratr=10.0 dip=90 dd=0 nr=1 nt=1 nx=1

join on
;
jset dip 45 dd 250 spac 0.5 num 30
jset dip 45 dd 180 spac 0.5 num 30

; zoning
gen edge 0.05
def mat_prop

  bulk_modulus = 20.90e9
  Shear_modulus = 10.78e9
  rock_density = 2600
  bcoh_ = 6e6
  bten_ = 8e6
  fric_angle = 28
  dilation_angle = 0

  ;Joint properties

  joint_kn = 9e9
  joint_ks = 6e9
  j_friction = 30
  j_tension = 0.0
  j_cohesion = 0.0
  j_ap0 = 1e-4 ;aperture at 0 normal stress

  ;fluid properties
  fluid_bulk_ = 3e6
  fluid_density_ = 1000.0
  fluid_viscosity_ = 0.001

end
@mat_prop

prop mat 1 bulk @bulk_modulus g @shear_modulus dens @rock_density bcoh @bcoh_
prop mat 1 bten @bten_ phi @fric_angle psi @dilation_angle
change mat 1 cons 2

;joint material properties for initial stress state, maintain constant aperture

prop jmat 1 jkn @joint_kn jks @joint_ks jfric @j_friction
prop jmat 1 jcoh @j_cohesion jten @j_tension azero @j_ap0 ares @j_ap0 amax @j_ap0

change jmat 1
; assigning fluid properties
fluid bulk @fluid_bulk_ density @fluid_density_ viscosity @fluid_viscosity_

; insitu stress and gradients
def set_insitu
;INPUT
depth = 2780 ; m
gravity_ = 9.81 ; m3/s

KH_max = 0.818 ; ration of maximum horizontal to vertical
Kh_min = 0.788 ; ratio of minimum horizontal to vertical
```

```
; Stresses at z= 0 of the model (positive)
szz0 = -rock_density*depth*gravity_ ; Vertical stress as from paper formula -rock_density*depth*gravity_
sxx0 = KH_max*szz0
syy0 = Kh_min*szz0

; fluid pressure at z = 0 (positive)
pp0 = fluid_density_*depth*gravity_ ; if calculated by fluid_density_*depth*gravity_ = 27.5 MPa

;gradients per m in positive z direction

szz_grad = rock_density*gravity_
syy_grad = kh_min*szz_grad
sxx_grad = kH_max*szz_grad
pp_grad = -fluid_density_ * gravity_

end
@set_insitu

;in-situ stress

insitu stress @sxx0 @syy0 @szz0 0. 0. 0. &
       zgrad @sxx_grad @syy_grad @szz_grad 0. 0. 0. nodisp
insitu pp @pp0 grad 0. 0. @pp_grad nodisp

;Boundary consitions

;bound xvel 0.0 yvel 0.0 zvel 0.0 range x 0.825
;bound xvel 0.0 yvel 0.0 zvel 0.0 range x -0.825
bound xvel 0.0 yvel 0.0 zvel 0.0 range z 0
bound xvel 0.0 yvel 0.0 zvel 0.0 range z -5
;bound xvel 0.0 yvel 0.0 zvel 0.0 range y 0.825
;bound xvel 0.0 yvel 0.0 zvel 0.0 range y -0.825

;bound stress -54e6 0 0 0,0,0 range x 0.825
;bound stress -54e6,0,0 0,0,0 range x -0.825
;bound stress 0 0 -66e6 0,0,0 range z 0
;bound stress 0 0 -66e6 0,0,0 range z -5
;bound stress 0,-52e6,0 0,0,0 range y 0.825
;bound stress 0,-52e6,0 0,0,0 range y -0.825

gravity 0 0 [-gravity_]
set flow off mech on
fluid bulk 0
hist unbal
set small
cyc 200

delete range cylinder end1 0.1 0.1 0.0 end2 0.1 0.1 -5.0 rad 0, 0.1

def reset_aperture
  local fp = flow_head
  loop while fp # 0
    local fpx = fp_fpx(fp)
    loop while fpx # 0
      fpx_apmech(fpx) = j_ap0
      fpx = fpx_next(fpx)
    end_loop
    fp = fp_next(fp)
  end_loop
end

def bh_setup

 ;maximum aperture
 j_ap_max = 30.0e-4
end
```

```
@bh_setup
;.....applying pressure in the borehole
;bou stress -28e6 -28e6 -28e6 0.0 0.0 0.0 range cylinder end1 0,0,0 end2 0,0,-5 rad 0,0.075


;
; reset displacements, apertures and time
reset disp jdisp
@reset_aperture
set time 0

; change joint materials to allow for joint opening
prop jmat 1 amax @j_ap_max

; flow only occurs through joints that have failed
set crack_flow on

; setup general fluid properties
fluid bulk @fluid_bulk_
fluid volmin 1e-3 areamin 0.25
set flow on mech on

; maximum number of mechanical steps per fluid step
set nmech 5



; inject into center
bound disch 0.106 range cyl end1 0 0 0 end2 0 0 -5 rad 0.0,0.1
; Notes


; point 1
his ndis 0.1 0.1 -2.5
his sdis 0.1 0.1 -2.5
his sstress 0.1 0.1 -2.5
his nstress 0.1 0.1 -2.5
his fluid_pp 0.1 0.1 -2.5
;point 2
his ndis -0.1 0.1 -2.5
his sdis -0.1 0.1 -2.5
his sstress -0.1 0.1 -2.5
his nstress -0.1 0.1 -2.5
his fluid_pp -0.1 0.1 -2.5
;point 3
his ndis -0.1 -0.1 -2.5
his sdis -0.1 -0.1 -2.5
his sstress -0.1 -0.1 -2.5
his nstress -0.1 -0.1 -2.5
his fluid_pp -0.1 -0.1 -2.5
;point 4
his ndis 0.1 -0.1 -2.5
his sdis 0.1 -0.1 -2.5
his sstress 0.1 -0.1 -2.5
his nstress 0.1 -0.1 -2.5
his fluid_pp 0.1 -0.1 -2.5
;point 5
his ndis 0.5 0.5 -2.5
his sdis 0.5 0.5 -2.5
his sstress 0.5 0.5 -2.5
his nstress 0.5 0.5 -2.5
his fluid_pp 0.5 0.5 -2.5
;xdis
his xdis 0.1 0.1 -2.5
his xdis -0.1 0.1 -2.5
his xdis 0.1 -0.1 -2.5
```

```
his xdis -0.1 -0.1 -2.5
his time
his unbal


cyc 500
save 40-BPM

-------------------------------------------

60 BPM

new
config fluid
set atol 0.002
poly tunnel rad=0.1 leng=0,5 ratr=10.0 dip=90 dd=0 nr=1 nt=1 nx=1

join on
;
jset dip 45 dd 250 spac 0.5 num 30
jset dip 45 dd 180 spac 0.5 num 30

; zoning
gen edge 0.05
def mat_prop

  bulk_modulus = 20.90e9
  Shear_modulus = 10.78e9
  rock_density = 2600
  bcoh_ = 6e6
  bten_ = 8e6
  fric_angle = 28
  dilation_angle = 0

  ;Joint properties

  joint_kn = 9e9
  joint_ks = 6e9
  j_friction = 30
  j_tension = 0.0
  j_cohesion = 0.0
  j_ap0 = 1e-4 ;aperture at 0 normal stress

  ;fluid properties
  fluid_bulk_ = 3e6
  fluid_density_ = 1000.0
  fluid_viscosity_ = 0.001

end
@mat_prop

prop mat 1 bulk @bulk_modulus g @shear_modulus dens @rock_density bcoh @bcoh_
prop mat 1 bten @bten_ phi @fric_angle psi @dilation_angle
change mat 1 cons 2

;joint material properties for initial stress state, maintain constant aperture

prop jmat 1 jkn @joint_kn jks @joint_ks jfric @j_friction
prop jmat 1 jcoh @j_cohesion jten @j_tension azero @j_ap0 ares @j_ap0 amax @j_ap0

change jmat 1
; assigning fluid properties
fluid bulk @fluid_bulk_ density @fluid_density_ viscosity @fluid_viscosity_

; insitu stress and gradients
def set_insitu
;INPUT
```

```
depth = 2780 ; m
gravity_ = 9.81 ; m3/s

KH_max = 0.818 ; ration of maximum horizontal to vertical
Kh_min = 0.788 ; ratio of minimum horizontal to vertical

; Stresses at z= 0 of the model (positive)
szz0 = -rock_density*depth*gravity_ ; Vertical stress as from paper formula -rock_density*depth*gravity_
sxx0 = KH_max*szz0
syy0 = Kh_min*szz0

; fluid pressure at z = 0 (positive)
pp0 = fluid_density_*depth*gravity_ ; if calculated by fluid_density_*depth*gravity_ = 27.5 MPa

;gradients per m in positive z direction

szz_grad = rock_density*gravity_
syy_grad = kh_min*szz_grad
sxx_grad = kH_max*szz_grad
pp_grad = -fluid_density_ * gravity_

end
@set_insitu

;in-situ stress

insitu stress @sxx0 @syy0 @szz0 0. 0. 0. &
      zgrad @sxx_grad @syy_grad @szz_grad 0. 0. 0. nodisp
insitu pp @pp0 grad 0. 0. @pp_grad nodisp

;Boundary consitions

;bound xvel 0.0 yvel 0.0 zvel 0.0 range x 0.825
;bound xvel 0.0 yvel 0.0 zvel 0.0 range x -0.825
;bound xvel 0.0 yvel 0.0 zvel 0.0 range z 0
;bound xvel 0.0 yvel 0.0 zvel 0.0 range z -5
;bound xvel 0.0 yvel 0.0 zvel 0.0 range y 0.825
;bound xvel 0.0 yvel 0.0 zvel 0.0 range y -0.825

;bound stress -54e6 0 0 0,0,0 range x 0.825
;bound stress -54e6,0,0 0,0,0 range x -0.825
;bound stress 0 0 -66e6 0,0,0 range z 0
;bound stress 0 0 -66e6 0,0,0 range z -5
;bound stress 0,-52e6,0 0,0,0 range y 0.825
;bound stress 0,-52e6,0 0,0,0 range y -0.825

gravity 0 0 [-gravity_]
set flow off mech on
fluid bulk 0
hist unbal
set small
cyc 200

delete range cylinder end1 0.1 0.1 0.0 end2 0.1 0.1 -5.0 rad 0, 0.1

def reset_aperture
  local fp = flow_head
  loop while fp # 0
    local fpx = fp_fpx(fp)
    loop while fpx # 0
      fpx_apmech(fpx) = j_ap0
      fpx = fpx_next(fpx)
    end_loop
    fp = fp_next(fp)
  end_loop
end
```

```
def bh_setup

 ;maximum aperture
 j_ap_max = 30.0e-4
end

@bh_setup
;.....applying pressure in the borehole
;bou stress -28e6 -28e6 -28e6 0.0 0.0 0.0 range cylinder end1 0,0,0 end2 0,0,-5 rad 0,0.075


;
; reset displacements, apertures and time
reset disp jdisp
@reset_aperture
set time 0

; change joint materials to allow for joint opening
prop jmat 1 amax @j_ap_max

; flow only occurs through joints that have failed
set crack_flow on

; setup general fluid properties
fluid bulk @fluid_bulk_
fluid volmin 1e-3 areamin 0.25
set flow on mech on

; maximum number of mechanical steps per fluid step
set nmech 5

; inject into center
bound disch 0.159 range cyl end1 0 0 0 end2 0 0 -5 rad 0.0,0.1

; Notes


; point 1
his ndis 0.1 0.1 -2.5
his sdis 0.1 0.1 -2.5
his sstress 0.1 0.1 -2.5
his nstress 0.1 0.1 -2.5
his fluid_pp 0.1 0.1 -2.5
;point 2
his ndis -0.1 0.1 -2.5
his sdis -0.1 0.1 -2.5
his sstress -0.1 0.1 -2.5
his nstress -0.1 0.1 -2.5
his fluid_pp -0.1 0.1 -2.5
;point 3
his ndis -0.1 -0.1 -2.5
his sdis -0.1 -0.1 -2.5
his sstress -0.1 -0.1 -2.5
his nstress -0.1 -0.1 -2.5
his fluid_pp -0.1 -0.1 -2.5
;point 4
his ndis 0.1 -0.1 -2.5
his sdis 0.1 -0.1 -2.5
his sstress 0.1 -0.1 -2.5
his nstress 0.1 -0.1 -2.5
his fluid_pp 0.1 -0.1 -2.5
;point 5
his ndis 0.5 0.5 -2.5
his sdis 0.5 0.5 -2.5
his sstress 0.5 0.5 -2.5
his nstress 0.5 0.5 -2.5
his fluid_pp 0.5 0.5 -2.5
```

```
;xdis
his xdis 0.1 0.1 -2.5
his xdis -0.1 0.1 -2.5
his xdis 0.1 -0.1 -2.5
his xdis -0.1 -0.1 -2.5
his time
his unbal


cyc 500
save 60-BPM

--------------------------------------
```

80 BPM

```
new
config fluid
set atol 0.002
poly tunnel rad=0.1 leng=0,5 ratr=10.0 dip=90 dd=0 nr=1 nt=1 nx=1

join on
;
jset dip 45 dd 250 spac 0.5 num 30
jset dip 45 dd 180 spac 0.5 num 30

; zoning
gen edge 0.05
def mat_prop

  bulk_modulus = 20.90e9
  Shear_modulus = 10.78e9
  rock_density = 2600
  bcoh_ = 6e6
  bten_ = 8e6
  fric_angle = 28
  dilation_angle = 0

  ;Joint properties

  joint_kn = 9e9
  joint_ks = 6e9
  j_friction = 30
  j_tension = 0.0
  j_cohesion = 0.0
  j_ap0 = 1e-4 ;aperture at 0 normal stress

  ;fluid properties
  fluid_bulk_ = 3e6
  fluid_density_ = 1000.0
  fluid_viscosity_ = 0.001

end
@mat_prop

prop mat 1 bulk @bulk_modulus g @shear_modulus dens @rock_density bcoh @bcoh_
prop mat 1 bten @bten_ phi @fric_angle psi @dilation_angle
change mat 1 cons 2

;joint material properties for initial stress state, maintain constant aperture

prop jmat 1 jkn @joint_kn jks @joint_ks jfric @j_friction
prop jmat 1 jcoh @j_cohesion jten @j_tension azero @j_ap0 ares @j_ap0 amax @j_ap0

change jmat 1
; assigning fluid properties
```

```
fluid bulk @fluid_bulk_ density @fluid_density_ viscosity @fluid_viscosity_

; insitu stress and gradients
def set_insitu
;INPUT
depth = 2780 ; m
gravity_ = 9.81 ; m3/s

KH_max = 0.818 ; ration of maximum horizontal to vertical
Kh_min = 0.788 ; ratio of minimum horizontal to vertical

; Stresses at z= 0 of the model (positive)
szz0 = -rock_density*depth*gravity_ ; Vertical stress as from paper formula -rock_density*depth*gravity_
sxx0 = KH_max*szz0
syy0 = Kh_min*szz0

; fluid pressure at z = 0 (positive)
pp0 = fluid_density_*depth*gravity_ ; if calculated by fluid_density_*depth*gravity_ = 27.5 MPa

;gradients per m in positive z direction

szz_grad = rock_density*gravity_
syy_grad = kh_min*szz_grad
sxx_grad = kH_max*szz_grad
pp_grad = -fluid_density_ * gravity_

end
@set_insitu

;in-situ stress

insitu stress @sxx0 @syy0 @szz0 0. 0. 0. &
      zgrad @sxx_grad @syy_grad @szz_grad 0. 0. 0. nodisp
insitu pp @pp0 grad 0. 0. @pp_grad nodisp

;Boundary consitions

;bound xvel 0.0 yvel 0.0 zvel 0.0 range x 0.825
;bound xvel 0.0 yvel 0.0 zvel 0.0 range x -0.825
bound xvel 0.0 yvel 0.0 zvel 0.0 range z 0
bound xvel 0.0 yvel 0.0 zvel 0.0 range z -5
;bound xvel 0.0 yvel 0.0 zvel 0.0 range y 0.825
;bound xvel 0.0 yvel 0.0 zvel 0.0 range y -0.825

;bound stress -54e6 0 0 0,0,0 range x 0.825
;bound stress -54e6,0,0 0,0,0 range x -0.825
;bound stress 0 0 -66e6 0,0,0 range z 0
;bound stress 0 0 -66e6 0,0,0 range z -5
;bound stress 0,-52e6,0 0,0,0 range y 0.825
;bound stress 0,-52e6,0 0,0,0 range y -0.825

gravity 0 0 [-gravity_]
set flow off mech on
fluid bulk 0
hist unbal
set small
cyc 200

delete range cylinder end1 0.1 0.1 0.0 end2 0.1 0.1 -5.0 rad 0, 0.1

def reset_aperture
  local fp = flow_head
  loop while fp # 0
    local fpx = fp_fpx(fp)
    loop while fpx # 0
      fpx_apmech(fpx) = j_ap0
      fpx = fpx_next(fpx)
```

```
    end_loop
    fp = fp_next(fp)
  end_loop
end

def bh_setup

 ;maximum aperture
 j_ap_max = 30.0e-4
end

@bh_setup
;.....applying pressure in the borehole
;bou stress -28e6 -28e6 -28e6 0.0 0.0 0.0 range cylinder end1 0,0,0 end2 0,0,-5 rad 0,0.075


;
; reset displacements, apertures and time
reset disp jdisp
@reset_aperture
set time 0

; change joint materials to allow for joint opening
prop jmat 1 amax @j_ap_max

; flow only occurs through joints that have failed
set crack_flow on

; setup general fluid properties
fluid bulk @fluid_bulk_
fluid volmin 1e-3 areamin 0.25
set flow on mech on

; maximum number of mechanical steps per fluid step
set nmech 5

; inject into center
; inject into center
bound disch 0.2127 range cyl end1 0 0 0 end2 0 0 -5 rad 0.0,0.1
; Notes


; point 1
his ndis 0.1 0.1 -2.5
his sdis 0.1 0.1 -2.5
his sstress 0.1 0.1 -2.5
his nstress 0.1 0.1 -2.5
his fluid_pp 0.1 0.1 -2.5
;point 2
his ndis -0.1 0.1 -2.5
his sdis -0.1 0.1 -2.5
his sstress -0.1 0.1 -2.5
his nstress -0.1 0.1 -2.5
his fluid_pp -0.1 0.1 -2.5
;point 3
his ndis -0.1 -0.1 -2.5
his sdis -0.1 -0.1 -2.5
his sstress -0.1 -0.1 -2.5
his nstress -0.1 -0.1 -2.5
his fluid_pp -0.1 -0.1 -2.5
;point 4
his ndis 0.1 -0.1 -2.5
his sdis 0.1 -0.1 -2.5
his sstress 0.1 -0.1 -2.5
his nstress 0.1 -0.1 -2.5
his fluid_pp 0.1 -0.1 -2.5
;point 5
```

```
his ndis 0.5 0.5 -2.5
his sdis 0.5 0.5 -2.5
his sstress 0.5 0.5 -2.5
his nstress 0.5 0.5 -2.5
his fluid_pp 0.5 0.5 -2.5
;xdis
his xdis 0.1 0.1 -2.5
his xdis -0.1 0.1 -2.5
his xdis 0.1 -0.1 -2.5
his xdis -0.1 -0.1 -2.5
his time
his unbal


cyc 500
save 80-BPM

------------------------------------------
```

Viscosity

1 cP

```
new
config fluid
set atol 0.002
poly tunnel rad=0.1 leng=0,5 ratr=10.0 dip=90 dd=0 nr=1 nt=1 nx=1

join on
;
jset dip 45 dd 250 spac 0.5 num 30
jset dip 45 dd 180 spac 0.5 num 30

; zoning
gen edge 0.06
def mat_prop

  bulk_modulus = 6e9
  Shear_modulus = 3.6e9
  rock_density = 2600
  bcoh_ = 13e6
  bten_ = 0.15
  fric_angle = 33
  dilation_angle = 4

  ;Joint properties

  joint_kn = 9e9
  joint_ks = 6e9
  j_friction = 30
  j_tension = 0.0
  j_cohesion = 0.0
  j_ap0 = 1e-4 ;aperture at 0 normal stress

  ;fluid properties
  fluid_bulk_ = 3e6
  fluid_density_ = 1000.0
  fluid_viscosity_ = 0.001

end
@mat_prop

prop mat 1 bulk @bulk_modulus g @shear_modulus dens @rock_density bcoh @bcoh_
prop mat 1 bten @bten_ phi @fric_angle psi @dilation_angle
change mat 1 cons 2
```

```
;joint material properties for initial stress state, maintain constant aperture

prop jmat 1 jkn @joint_kn jks @joint_ks jfric @j_friction
prop jmat 1 jcoh @j_cohesion jten @j_tension azero @j_ap0 ares @j_ap0 amax @j_ap0

change jmat 1
; assigning fluid properties
fluid bulk @fluid_bulk_ density @fluid_density_ viscosity @fluid_viscosity_

; insitu stress and gradients
def set_insitu
;INPUT
depth = 2780 ; m
gravity_ = 9.81 ; m3/s

KH_max = 0.818 ; ration of maximum horizontal to vertical
Kh_min = 0.788 ; ratio of minimum horizontal to vertical

; Stresses at z= 0 of the model (positive)
szz0 = -rock_density*depth*gravity_ ; Vertical stress as from paper formula -rock_density*depth*gravity_
sxx0 = KH_max*szz0
syy0 = Kh_min*szz0

; fluid pressure at z = 0 (positive)
pp0 = fluid_density_*depth*gravity_ ; if calculated by fluid_density_*depth*gravity_ = 27.5 MPa

;gradients per m in positive z direction

szz_grad = rock_density*gravity_
syy_grad = kh_min*szz_grad
sxx_grad = kH_max*szz_grad
pp_grad = -fluid_density_ * gravity_

end
@set_insitu

;in-situ stress

insitu stress @sxx0 @syy0 @szz0 0. 0. 0. &
      zgrad @sxx_grad @syy_grad @szz_grad 0. 0. 0. nodisp
insitu pp @pp0 grad 0. 0. @pp_grad nodisp

;Boundary consitions

;bound xvel 0.0 yvel 0.0 zvel 0.0 range x 0.085
;bound xvel 0.0 yvel 0.0 zvel 0.0 range x -0.085
;bound xvel 0.0 yvel 0.0 zvel 0.0 range z 0
;bound xvel 0.0 yvel 0.0 zvel 0.0 range z -5
;bound xvel 0.0 yvel 0.0 zvel 0.0 range y 0.085
;bound xvel 0.0 yvel 0.0 zvel 0.0 range y -0.085

;bound stress -54e6 0 0 0,0,0 range x 1.1
;bound stress -54e6,0,0 0,0,0 range x -1.1
;bound stress 0 0 -66e6 0,0,0 range z 0
;bound stress 0 0 -66e6 0,0,0 range z -5
;bound stress 0,-52e6,0 0,0,0 range y 1.1
;bound stress 0,-52e6,0 0,0,0 range y -1.1

gravity 0 0 [-gravity_]
set flow off mech on
fluid bulk 0
hist unbal
set small
cyc 200

delete range x -0.1,0.1 y -0.1,0.1 z 0,-5
```

```
def reset_aperture
  local fp = flow_head
  loop while fp # 0
    local fpx = fp_fpx(fp)
    loop while fpx # 0
      fpx_apmech(fpx) = j_ap0
      fpx = fpx_next(fpx)
    end_loop
    fp = fp_next(fp)
  end_loop
end

def bh_setup

 ;maximum aperture
 j_ap_max = 30.0e-4
end

@bh_setup
;.....applying pressure in the borehole

;boun str -28e6,-28e6,-28e6 0,0,0 range cyl end1 0 0 0.0 end2 0 0 -5 rad 0.0,0.1
;
; reset displacements, apertures and time
reset disp jdisp
@reset_aperture
set time 0

; change joint materials to allow for joint opening
prop jmat 1 amax @j_ap_max

; flow only occurs through joints that have failed
set crack_flow on

; setup general fluid properties
fluid bulk @fluid_bulk_
fluid volmin 1e-3 areamin 0.25
set flow on mech on

; maximum number of mechanical steps per fluid step
set nmech 5

; inject into center
bound disch 0.053 range cyl end1 0 0 0 end2 0 0 -5 rad 0.0,0.1

; Notes
;the problem is not the whole data file but method of injection
; point 1
his ndis 0.1 0.1 -2.5
his sdis 0.1 0.1 -2.5
his sstress 0.1 0.1 -2.5
his nstress 0.1 0.1 -2.5
his fluid_pp 0.1 0.1 -2.5
;point 2
his ndis -0.1 0.1 -2.5
his sdis -0.1 0.1 -2.5
his sstress -0.1 0.1 -2.5
his nstress -0.1 0.1 -2.5
his fluid_pp -0.1 0.1 -2.5
;point 3
his ndis -0.1 -0.1 -2.5
his sdis -0.1 -0.1 -2.5
his sstress -0.1 -0.1 -2.5
his nstress -0.1 -0.1 -2.5
his fluid_pp -0.1 -0.1 -2.5
;point 4
his ndis 0.1 -0.1 -2.5
```

```
his sdis 0.1 -0.1 -2.5
his sstress 0.1 -0.1 -2.5
his nstress 0.1 -0.1 -2.5
his fluid_pp 0.1 -0.1 -2.5
;point 5
his ndis 0.5 0.5 -2.5
his sdis 0.5 0.5 -2.5
his sstress 0.5 0.5 -2.5
his nstress 0.5 0.5 -2.5
his fluid_pp 0.5 0.5 -2.5
;xdis
his xdis 0.1 0.1 -2.5
his xdis -0.1 0.1 -2.5
his xdis 0.1 -0.1 -2.5
his xdis -0.1 -0.1 -2.5
his time
his unbal


cyc 600
save 1-cP
```

----

100 cP

```
new
config fluid
set atol 0.002
poly tunnel rad=0.1 leng=0,5 ratr=10.0 dip=90 dd=0 nr=1 nt=1 nx=1

join on
;
jset dip 45 dd 250 spac 0.5 num 30
jset dip 45 dd 180 spac 0.5 num 30

; zoning
gen edge 0.06
def mat_prop

  bulk_modulus = 6e9
  Shear_modulus = 3.6e9
  rock_density = 2600
  bcoh_ = 13e6
  bten_ = 0.15
  fric_angle = 33
  dilation_angle = 4

  ;Joint properties

  joint_kn = 9e9
  joint_ks = 6e9
  j_friction = 30
  j_tension = 0.0
  j_cohesion = 0.0
  j_ap0 = 1e-4 ;aperture at 0 normal stress

  ;fluid properties
  fluid_bulk_ = 3e6
  fluid_density_ = 1000.0
  fluid_viscosity_ = 0.1

end
@mat_prop

prop mat 1 bulk @bulk_modulus g @shear_modulus dens @rock_density bcoh @bcoh_
prop mat 1 bten @bten_ phi @fric_angle psi @dilation_angle
```

```
change mat 1 cons 2

;joint material properties for initial stress state, maintain constant aperture

prop jmat 1 jkn @joint_kn jks @joint_ks jfric @j_friction
prop jmat 1 jcoh @j_cohesion jten @j_tension azero @j_ap0 ares @j_ap0 amax @j_ap0

change jmat 1
; assigning fluid properties
fluid bulk @fluid_bulk_ density @fluid_density_ viscosity @fluid_viscosity_

; insitu stress and gradients
def set_insitu
;INPUT
depth = 2780 ; m
gravity_ = 9.81 ; m3/s

KH_max = 0.818 ; ration of maximum horizontal to vertical
Kh_min = 0.788 ; ratio of minimum horizontal to vertical

; Stresses at z= 0 of the model (positive)
szz0 = -rock_density*depth*gravity_ ; Vertical stress as from paper formula -rock_density*depth*gravity_
sxx0 = KH_max*szz0
syy0 = Kh_min*szz0

; fluid pressure at z = 0 (positive)
pp0 = fluid_density_*depth*gravity_ ; if calculated by fluid_density_*depth*gravity_ = 27.5 MPa

;gradients per m in positive z direction

szz_grad = rock_density*gravity_
syy_grad = kh_min*szz_grad
sxx_grad = kH_max*szz_grad
pp_grad = -fluid_density_ * gravity_

end
@set_insitu

;in-situ stress

insitu stress @sxx0 @syy0 @szz0 0. 0. 0. &
      zgrad @sxx_grad @syy_grad @szz_grad 0. 0. 0. nodisp
insitu pp @pp0 grad 0. 0. @pp_grad nodisp

;Boundary consitions

;bound xvel 0.0 yvel 0.0 zvel 0.0 range x 0.085
;bound xvel 0.0 yvel 0.0 zvel 0.0 range x -0.085
;bound xvel 0.0 yvel 0.0 zvel 0.0 range z 0
;bound xvel 0.0 yvel 0.0 zvel 0.0 range z -5
;bound xvel 0.0 yvel 0.0 zvel 0.0 range y 0.085
;bound xvel 0.0 yvel 0.0 zvel 0.0 range y -0.085

;bound stress -54e6 0 0 0,0,0 range x 1.1
;bound stress -54e6,0,0 0,0,0 range x -1.1
;bound stress 0 0 -66e6 0,0,0 range z 0
;bound stress 0 0 -66e6 0,0,0 range z -5
;bound stress 0,-52e6,0 0,0,0 range y 1.1
;bound stress 0,-52e6,0 0,0,0 range y -1.1

gravity 0 0 [-gravity_]
set flow off mech on
fluid bulk 0
hist unbal
set small
cyc 200
```

```
delete range x -0.1,0.1 y -0.1,0.1 z 0,-5

def reset_aperture
  local fp = flow_head
  loop while fp # 0
    local fpx = fp_fpx(fp)
    loop while fpx # 0
      fpx_apmech(fpx) = j_ap0
      fpx = fpx_next(fpx)
    end_loop
    fp = fp_next(fp)
  end_loop
end

def bh_setup

 ;maximum aperture
 j_ap_max = 30.0e-4
end

@bh_setup
;.....applying pressure in the borehole

;boun str -28e6,-28e6,-28e6 0,0,0 range cyl end1 0 0 0.0 end2 0 0 -5 rad 0.0,0.1
;
; reset displacements, apertures and time
reset disp jdisp
@reset_aperture
set time 0

; change joint materials to allow for joint opening
prop jmat 1 amax @j_ap_max

; flow only occurs through joints that have failed
set crack_flow on

; setup general fluid properties
fluid bulk @fluid_bulk_
fluid volmin 1e-3 areamin 0.25
set flow on mech on

; maximum number of mechanical steps per fluid step
set nmech 5

; inject into center
bound disch 0.053 range cyl end1 0 0 0 end2 0 0 -5 rad 0.0,0.1

; Notes
;the problem is not the whole data file but method of injection
; point 1
his ndis 0.1 0.1 -2.5
his sdis 0.1 0.1 -2.5
his sstress 0.1 0.1 -2.5
his nstress 0.1 0.1 -2.5
his fluid_pp 0.1 0.1 -2.5
;point 2
his ndis -0.1 0.1 -2.5
his sdis -0.1 0.1 -2.5
his sstress -0.1 0.1 -2.5
his nstress -0.1 0.1 -2.5
his fluid_pp -0.1 0.1 -2.5
;point 3
his ndis -0.1 -0.1 -2.5
his sdis -0.1 -0.1 -2.5
his sstress -0.1 -0.1 -2.5
his nstress -0.1 -0.1 -2.5
his fluid_pp -0.1 -0.1 -2.5
```

```
;point 4
his ndis 0.1 -0.1 -2.5
his sdis 0.1 -0.1 -2.5
his sstress 0.1 -0.1 -2.5
his nstress 0.1 -0.1 -2.5
his fluid_pp 0.1 -0.1 -2.5
;point 5
his ndis 0.5 0.5 -2.5
his sdis 0.5 0.5 -2.5
his sstress 0.5 0.5 -2.5
his nstress 0.5 0.5 -2.5
his fluid_pp 0.5 0.5 -2.5
;xdis
his xdis 0.1 0.1 -2.5
his xdis -0.1 0.1 -2.5
his xdis 0.1 -0.1 -2.5
his xdis -0.1 -0.1 -2.5
his time
his unbal


cyc 600
save 100-cP
--------------------------------
```

1000 cP

```
new
config fluid
set atol 0.002
poly tunnel rad=0.1 leng=0,5 ratr=10.0 dip=90 dd=0 nr=1 nt=1 nx=1

join on
;
jset dip 45 dd 250 spac 0.5 num 30
jset dip 45 dd 180 spac 0.5 num 30

; zoning
gen edge 0.06
def mat_prop

  bulk_modulus = 6e9
  Shear_modulus = 3.6e9
  rock_density = 2600
  bcoh_ = 13e6
  bten_ = 0.15
  fric_angle = 33
  dilation_angle = 4

  ;Joint properties

  joint_kn = 9e9
  joint_ks = 6e9
  j_friction = 30
  j_tension = 0.0
  j_cohesion = 0.0
  j_ap0 = 1e-4 ;aperture at 0 normal stress

  ;fluid properties
  fluid_bulk_ = 3e6
  fluid_density_ = 1000.0
  fluid_viscosity_ = 1.0

end
@mat_prop
```

```
prop mat 1 bulk @bulk_modulus g @shear_modulus dens @rock_density bcoh @bcoh_
prop mat 1 bten @bten_ phi @fric_angle psi @dilation_angle
change mat 1 cons 2

;joint material properties for initial stress state, maintain constant aperture

prop jmat 1 jkn @joint_kn jks @joint_ks jfric @j_friction
prop jmat 1 jcoh @j_cohesion jten @j_tension azero @j_ap0 ares @j_ap0 amax @j_ap0

change jmat 1
; assigning fluid properties
fluid bulk @fluid_bulk_ density @fluid_density_ viscosity @fluid_viscosity_

; insitu stress and gradients
def set_insitu
;INPUT
depth = 2780 ; m
gravity_ = 9.81 ; m3/s

KH_max = 0.818 ; ration of maximum horizontal to vertical
Kh_min = 0.788 ; ratio of minimum horizontal to vertical

; Stresses at z= 0 of the model (positive)
szz0 = -rock_density*depth*gravity_ ; Vertical stress as from paper formula -rock_density*depth*gravity_
sxx0 = KH_max*szz0
syy0 = Kh_min*szz0

; fluid pressure at z = 0 (positive)
pp0 = fluid_density_*depth*gravity_ ; if calculated by fluid_density_*depth*gravity_ = 27.5 MPa

;gradients per m in positive z direction

szz_grad = rock_density*gravity_
syy_grad = kh_min*szz_grad
sxx_grad = kH_max*szz_grad
pp_grad = -fluid_density_ * gravity_

end
@set_insitu

;in-situ stress

insitu stress @sxx0 @syy0 @szz0 0. 0. 0. &
      zgrad @sxx_grad @syy_grad @szz_grad 0. 0. 0. nodisp
insitu pp @pp0 grad 0. 0. @pp_grad nodisp

;Boundary consitions

;bound xvel 0.0 yvel 0.0 zvel 0.0 range x 0.085
;bound xvel 0.0 yvel 0.0 zvel 0.0 range x -0.085
;bound xvel 0.0 yvel 0.0 zvel 0.0 range z 0
;bound xvel 0.0 yvel 0.0 zvel 0.0 range z -5
;bound xvel 0.0 yvel 0.0 zvel 0.0 range y 0.085
;bound xvel 0.0 yvel 0.0 zvel 0.0 range y -0.085

;bound stress -54e6 0 0 0,0,0 range x 1.1
;bound stress -54e6,0,0 0,0,0 range x -1.1
;bound stress 0 0 -66e6 0,0,0 range z 0
;bound stress 0 0 -66e6 0,0,0 range z -5
;bound stress 0,-52e6,0 0,0,0 range y 1.1
;bound stress 0,-52e6,0 0,0,0 range y -1.1

gravity 0 0 [-gravity_]
set flow off mech on
fluid bulk 0
hist unbal
set small
```

```
cyc 200

delete range cyl end1 0 0 0 end2 0 0 -5 rad 0.0,0.1

def reset_aperture
  local fp = flow_head
  loop while fp # 0
    local fpx = fp_fpx(fp)
    loop while fpx # 0
      fpx_apmech(fpx) = j_ap0
      fpx = fpx_next(fpx)
    end_loop
    fp = fp_next(fp)
  end_loop
end

def bh_setup

 ;maximum aperture
 j_ap_max = 30.0e-4
end

@bh_setup
;.....applying pressure in the borehole

;boun str -28e6,-28e6,-28e6 0,0,0 range cyl end1 0 0 0.0 end2 0 0 -5 rad 0.0,0.1
;
; reset displacements, apertures and time
reset disp jdisp
@reset_aperture
set time 0

; change joint materials to allow for joint opening
prop jmat 1 amax @j_ap_max

; flow only occurs through joints that have failed
set crack_flow on

; setup general fluid properties
fluid bulk @fluid_bulk_
fluid volmin 1e-3 areamin 0.25
set flow on mech on

; maximum number of mechanical steps per fluid step
set nmech 5

; inject into center
bound disch 0.053 range cyl end1 0 0 0 end2 0 0 -5 rad 0.0,0.1

; Notes
;the problem is not the whole data file but method of injection
; point 1
his ndis 0.1 0.1 -2.5
his sdis 0.1 0.1 -2.5
his sstress 0.1 0.1 -2.5
his nstress 0.1 0.1 -2.5
his fluid_pp 0.1 0.1 -2.5
;point 2
his ndis -0.1 0.1 -2.5
his sdis -0.1 0.1 -2.5
his sstress -0.1 0.1 -2.5
his nstress -0.1 0.1 -2.5
his fluid_pp -0.1 0.1 -2.5
;point 3
his ndis -0.1 -0.1 -2.5
his sdis -0.1 -0.1 -2.5
his sstress -0.1 -0.1 -2.5
```

```
his nstress -0.1 -0.1 -2.5
his fluid_pp -0.1 -0.1 -2.5
;point 4
his ndis 0.1 -0.1 -2.5
his sdis 0.1 -0.1 -2.5
his sstress 0.1 -0.1 -2.5
his nstress 0.1 -0.1 -2.5
his fluid_pp 0.1 -0.1 -2.5
;point 5
his ndis 0.5 0.5 -2.5
his sdis 0.5 0.5 -2.5
his sstress 0.5 0.5 -2.5
his nstress 0.5 0.5 -2.5
his fluid_pp 0.5 0.5 -2.5
;xdis
his xdis 0.1 0.1 -2.5
his xdis -0.1 0.1 -2.5
his xdis 0.1 -0.1 -2.5
his xdis -0.1 -0.1 -2.5
his time
his unbal


cyc 600
save 1000-cP
```

10000 cP

```
new
config fluid
set atol 0.002
poly tunnel rad=0.1 leng=0,5 ratr=10.0 dip=90 dd=0 nr=1 nt=1 nx=1

join on
;
jset dip 45 dd 250 spac 0.5 num 30
jset dip 45 dd 180 spac 0.5 num 30

; zoning
gen edge 0.06
def mat_prop

  bulk_modulus = 6e9
  Shear_modulus = 3.6e9
  rock_density = 2600
  bcoh_ = 13e6
  bten_ = 0.15
  fric_angle = 33
  dilation_angle = 4

  ;Joint properties

  joint_kn = 9e9
  joint_ks = 6e9
  j_friction = 30
  j_tension = 0.0
  j_cohesion = 0.0
  j_ap0 = 1e-4 ;aperture at 0 normal stress

  ;fluid properties
  fluid_bulk_ = 3e6
  fluid_density_ = 1000.0
  fluid_viscosity_ = 10.0

end
```

```
@mat_prop

prop mat 1 bulk @bulk_modulus g @shear_modulus dens @rock_density bcoh @bcoh_
prop mat 1 bten @bten_ phi @fric_angle psi @dilation_angle
change mat 1 cons 2

;joint material properties for initial stress state, maintain constant aperture

prop jmat 1 jkn @joint_kn jks @joint_ks jfric @j_friction
prop jmat 1 jcoh @j_cohesion jten @j_tension azero @j_ap0 ares @j_ap0 amax @j_ap0

change jmat 1
; assigning fluid properties
fluid bulk @fluid_bulk_ density @fluid_density_ viscosity @fluid_viscosity_

; insitu stress and gradients
def set_insitu
;INPUT
depth = 2780 ; m
gravity_ = 9.81 ; m3/s

KH_max = 0.818 ; ration of maximum horizontal to vertical
Kh_min = 0.788 ; ratio of minimum horizontal to vertical

; Stresses at z= 0 of the model (positive)
szz0 = -rock_density*depth*gravity_ ; Vertical stress as from paper formula -rock_density*depth*gravity_
sxx0 = KH_max*szz0
syy0 = Kh_min*szz0

; fluid pressure at z = 0 (positive)
pp0 = fluid_density_*depth*gravity_ ; if calculated by fluid_density_*depth*gravity_ = 27.5 MPa

;gradients per m in positive z direction

szz_grad = rock_density*gravity_
syy_grad = kh_min*szz_grad
sxx_grad = kH_max*szz_grad
pp_grad = -fluid_density_ * gravity_

end
@set_insitu

;in-situ stress

insitu stress @sxx0 @syy0 @szz0 0. 0. 0. &
      zgrad @sxx_grad @syy_grad @szz_grad 0. 0. 0. nodisp
insitu pp @pp0 grad 0. 0. @pp_grad nodisp

;Boundary consitions

;bound xvel 0.0 yvel 0.0 zvel 0.0 range x 0.085
;bound xvel 0.0 yvel 0.0 zvel 0.0 range x -0.085
;bound xvel 0.0 yvel 0.0 zvel 0.0 range z 0
;bound xvel 0.0 yvel 0.0 zvel 0.0 range z -5
;bound xvel 0.0 yvel 0.0 zvel 0.0 range y 0.085
;bound xvel 0.0 yvel 0.0 zvel 0.0 range y -0.085

;bound stress -54e6 0 0 0,0,0 range x 1.1
;bound stress -54e6,0,0 0,0,0 range x -1.1
;bound stress 0 0 -66e6 0,0,0 range z 0
;bound stress 0 0 -66e6 0,0,0 range z -5
;bound stress 0,-52e6,0 0,0,0 range y 1.1
;bound stress 0,-52e6,0 0,0,0 range y -1.1

gravity 0 0 [-gravity_]
set flow off mech on
fluid bulk 0
```

```
hist unbal
set small
cyc 200

delete range cyl end1 0 0 0 end2 0 0 -5 rad 0.0,0.1

def reset_aperture
  local fp = flow_head
  loop while fp # 0
    local fpx = fp_fpx(fp)
    loop while fpx # 0
      fpx_apmech(fpx) = j_ap0
      fpx = fpx_next(fpx)
    end_loop
    fp = fp_next(fp)
  end_loop
end

def bh_setup

 ;maximum aperture
 j_ap_max = 30.0e-4
end

@bh_setup
;.....applying pressure in the borehole

;boun str -28e6,-28e6,-28e6 0,0,0 range cyl end1 0 0 0.0 end2 0 0 -5 rad 0.0,0.1
;
; reset displacements, apertures and time
reset disp jdisp
@reset_aperture
set time 0

; change joint materials to allow for joint opening
prop jmat 1 amax @j_ap_max

; flow only occurs through joints that have failed
set crack_flow on

; setup general fluid properties
fluid bulk @fluid_bulk_
fluid volmin 1e-3 areamin 0.25
set flow on mech on

; maximum number of mechanical steps per fluid step
set nmech 5

; inject into center
bound disch 0.001 range cyl end1 0 0 0 end2 0 0 -5 rad 0.0,0.1

; Notes
;the problem is not the whole data file but method of injection
; point 1
his ndis 0.1 0.1 -2.5
his sdis 0.1 0.1 -2.5
his sstress 0.1 0.1 -2.5
his nstress 0.1 0.1 -2.5
his fluid_pp 0.1 0.1 -2.5
;point 2
his ndis -0.1 0.1 -2.5
his sdis -0.1 0.1 -2.5
his sstress -0.1 0.1 -2.5
his nstress -0.1 0.1 -2.5
his fluid_pp -0.1 0.1 -2.5
;point 3
his ndis -0.1 -0.1 -2.5
```

```
his sdis -0.1 -0.1 -2.5
his sstress -0.1 -0.1 -2.5
his nstress -0.1 -0.1 -2.5
his fluid_pp -0.1 -0.1 -2.5
;point 4
his ndis 0.1 -0.1 -2.5
his sdis 0.1 -0.1 -2.5
his sstress 0.1 -0.1 -2.5
his nstress 0.1 -0.1 -2.5
his fluid_pp 0.1 -0.1 -2.5
;point 5
his ndis 0.5 0.5 -2.5
his sdis 0.5 0.5 -2.5
his sstress 0.5 0.5 -2.5
his nstress 0.5 0.5 -2.5
his fluid_pp 0.5 0.5 -2.5
;xdis
his xdis 0.1 0.1 -2.5
his xdis -0.1 0.1 -2.5
his xdis 0.1 -0.1 -2.5
his xdis -0.1 -0.1 -2.5
his time
his unbal


cyc 600
save 10000-cP
---------------------------------------------
```

Paper 3

Regional model with fractures

```
new
set atol 0.002
config gw
;geometry of the model
poly brick -100,100 -100,100 -40,40
group block 'outermodel' range z -40,40
hide range group 'outermodel'
def fault_id
 ; MB_id = 1
  Major_f = 2
  NW = 3
  SE = 4
end
@fault_id
;inner model of the borehole
poly tunnel rad 1.0 leng=0,10 ratr= 9.0 dip=90 dd=0 nr=1 nt=1 nx=1
join on
group block 'innermodel'
;mark region 1 range x -1.0 1.0 y -1.0 1.0 z 0, -10
seek
;

;;Mountain bridge fault
;jset dip 90 dd 95 origin 800 100 -400 id @MB_id
;major faults paralell to MB fault
jset dip 90 dd 95 spac 75 num 4 origin 15 0 0 id @Major_f
hide range group 'outermodel'
;jset dip 80 dd 80 spac 8 num 2 origin -2.5 -2.5 -2.5 id @NW
;jset dip 45 dd 0 spac 5 num 8 origin 1 1 1 id @SE
seek
```

```
;

;
;zoning
hide range group 'outermodel'
gen edge 2
seek
hide range group 'innermodel'
gen edge 10
seek

save zoned

.............................



rest zoned
def mat_prop

  bulk_modulus = 20.90e9
  Shear_modulus = 10.78e9
  rock_density = 2600
  bcoh_ = 6e6
  bten_ = 8e6
  fric_angle = 28
  dilation_angle = 0

  ;Joint properties

  joint_kn = 9e11
  joint_ks = 6e11
  j_friction = 30
  j_tension = 0.0
  j_cohesion = 0.0
  j_ap0 = 1e-4 ;aperture at 0 normal stress

  ;fluid properties
  fluid_bulk_ = 3e6
  fluid_density_ = 1000.0
  fluid_viscosity_ = 0.001

end
@mat_prop

prop mat 1 bulk @bulk_modulus g @shear_modulus dens @rock_density bcoh @bcoh_
prop mat 1 bten @bten_ phi @fric_angle psi @dilation_angle
change mat 1 cons 2

;joint material properties for initial stress state, maintain constant aperture

prop jmat 1 jkn @joint_kn jks @joint_ks jfric @j_friction
prop jmat 1 jcoh @j_cohesion jten @j_tension azero @j_ap0 ares @j_ap0 amax @j_ap0

change jmat 1
; assigning fluid properties
fluid bulk @fluid_bulk_ density @fluid_density_ viscosity @fluid_viscosity_

;insitu stress and gradients
def set_insitu
;INPUT
depth = 2780 ; m
gravity_ = 9.81 ; m3/s

KH_max = 0.818 ; ration of maximum horizontal to vertical
Kh_min = 0.788 ; ratio of minimum horizontal to vertical
```

```
; Stresses at z= 0 of the model (positive)
szz0 = -rock_density*depth*gravity_ ; Vertical stress as from paper formula -rock_density*depth*gravity_
sxx0 = KH_max*szz0
syy0 = Kh_min*szz0

; fluid pressure at z = 0 (positive)
pp0 = fluid_density_*depth*gravity_ ; if calculated by fluid_density_*depth*gravity_ = 27.5 MPa

;gradients per m in positive z direction

szz_grad = rock_density*gravity_
syy_grad = kh_min*szz_grad
sxx_grad = kH_max*szz_grad
pp_grad = -fluid_density_ * gravity_

end
@set_insitu

;in-situ stress

insitu stress @sxx0 @syy0 @szz0 0. 0. 0. &
      zgrad @sxx_grad @syy_grad @szz_grad 0. 0. 0. nodisp
insitu pp @pp0 grad 0. 0. @pp_grad nodisp

;Boundary stresses are not includes as proble area is very far from the boundary
;Boundary stresses

;top of the model (szz40= rock_density*gravity)*(z = 2780-40 = 2740)
def boun_stress
 szz40 = -69886440
 syy40 = Kh_min * 69886440
 sxx40 = KH_max * 69886440
end
@boun_stress
bou stress @sxx40 @syy40 @szz40 0 0 0 range z 0.0
;Boundary consitions

bou xvel 0.0 yvel 0.0 zvel 0.0 range x -10
bou xvel 0.0 yvel 0.0 zvel 0.0 range x 10
bou xvel 0.0 yvel 0.0 zvel 0.0 range y -10
bou xvel 0.0 yvel 0.0 zvel 0.0 range y 10
bou xvel 0.0 yvel 0.0 zvel 0.0 range z -10

gravity 0 0 [-gravity_]
;initial equilibrium- mechanical
set flow off mech on
fluid bulk 0.0
hist unbal
;cyc 500
;save mech-equ
;initial equilibrium- fluid
;set flow on mech off
;fluid bulk @fluid_bulk_
;set small
;cyc 500
;save fluid-equ

;set flow on mech on
;fluid bulk @fluid_bulk_
;;set nmech 10
his time

step 200
save initial

............................
```

```
rest initial
reset disp jdisp
hide range group 'outermodel'
;SET log on
LIST brick -10 10 -10 10 -10 10 for
delete range x -1.0 1.0 y -1.0 1.0 z 0, -10

; Function to extrapolate zone stresses to gridpoint extra variable
; for plotting of smooth contours

; Vertex extra 1: maximum compressive stress, s1 (positive compression)
; Vertex extra 2: minimum compressive stress, s3 (positive compression)
==================================================
def plot_stress

  ; first initialize to 0
  local bi = block_head
  loop while bi # 0
    local gpi = b_gp(bi)
    loop while gpi # 0
      gp_extra(gpi,1) = 0.0 ; s1
      gp_extra(gpi,2) = 0.0 ; s3
      gp_extra(gpi,3) = 0.0 ; volume sum
      gpi = gp_next(gpi)
    end_loop
    bi = b_next(bi)
  end_loop

  ; sum stresses and volumes
  bi = block_head
  loop while bi # 0
    local zi = b_zone(bi)
    loop while zi # 0
      local zs1 = -z_sig1(zi)
      local zs3 = -z_sig3(zi)
      local zvol = z_vol(zi)
      loop local zgp (1,4)
        gpi = z_gp(zi,zgp)
        gp_extra(gpi,1) = gp_extra(gpi,1) + zs1*zvol
        gp_extra(gpi,2) = gp_extra(gpi,2) + zs3*zvol
        gp_extra(gpi,3) = gp_extra(gpi,3) + zvol
      end_loop
      zi = z_next(zi)
    end_loop
    bi = b_next(bi)
  end_loop

  ; get weighted average
  bi = block_head
  loop while bi # 0
    gpi = b_gp(bi)
    loop while gpi # 0
      local vol_sum = gp_extra(gpi,3)
      if vol_sum > 0.0
        gp_extra(gpi,1) = gp_extra(gpi,1) / vol_sum
        gp_extra(gpi,2) = gp_extra(gpi,2) / vol_sum
      end_if
      gpi = gp_next(gpi)
    end_loop
    bi = b_next(bi)
  end_loop
end
==========================================
@plot_stress
plot create plot stress
plot axes
```

```
plot gpcontour gp
step 400
seek
save BH
```

Regional model without fractures

```
new
set atol 0.002
config gw
;geometry of the model
poly brick -100,100 -100,100 -40,40

gen edge 12
;seek
;hide range group 'innermodel'
;gen edge 10
;seek

save zoned

rest zoned
def mat_prop

  bulk_modulus = 20.90e9
  Shear_modulus = 10.78e9
  rock_density = 2600
  bcoh_ = 6e6
  bten_ = 8e6
  fric_angle = 28
  dilation_angle = 0

  ;Joint properties

  joint_kn = 9e11
  joint_ks = 6e11
  j_friction = 30
  j_tension = 0.0
  j_cohesion = 0.0
  j_ap0 = 1e-4 ;aperture at 0 normal stress

  ;fluid properties
  fluid_bulk_ = 3e6
  fluid_density_ = 1000.0
  fluid_viscosity_ = 0.001

end
@mat_prop

prop mat 1 bulk @bulk_modulus g @shear_modulus dens @rock_density bcoh @bcoh_
prop mat 1 bten @bten_ phi @fric_angle psi @dilation_angle
change mat 1 cons 2

;joint material properties for initial stress state, maintain constant aperture

prop jmat 1 jkn @joint_kn jks @joint_ks jfric @j_friction
prop jmat 1 jcoh @j_cohesion jten @j_tension azero @j_ap0 ares @j_ap0 amax @j_ap0

change jmat 1
; assigning fluid properties
fluid bulk @fluid_bulk_ density @fluid_density_ viscosity @fluid_viscosity_

;insitu stress and gradients
def set_insitu
;INPUT
```

```
depth = 2780 ; m
gravity_ = 9.81 ; m3/s

KH_max = 0.818 ; ration of maximum horizontal to vertical
Kh_min = 0.788 ; ratio of minimum horizontal to vertical

; Stresses at z= 0 of the model (positive)
szz0 = -rock_density*depth*gravity_ ; Vertical stress as from paper formula -rock_density*depth*gravity_
sxx0 = KH_max*szz0
syy0 = Kh_min*szz0

; fluid pressure at z = 0 (positive)
pp0 = fluid_density_*depth*gravity_ ; if calculated by fluid_density_*depth*gravity_ = 27.5 MPa

;gradients per m in positive z direction

szz_grad = rock_density*gravity_
syy_grad = kh_min*szz_grad
sxx_grad = kH_max*szz_grad
pp_grad = -fluid_density_ * gravity_

end
@set_insitu

;in-situ stress

insitu stress @sxx0 @syy0 @szz0 0. 0. 0. &
      zgrad @sxx_grad @syy_grad @szz_grad 0. 0. 0. nodisp
insitu pp @pp0 grad 0. 0. @pp_grad nodisp

;Boundary stresses are not includes as proble area is very far from the boundary
;Boundary stresses

;top of the model (szz40= rock_density*gravity)*(z = 2780-40 = 2740)
def boun_stress
 szz40 = -69886440
 syy40 = Kh_min * 69886440
 sxx40 = KH_max * 69886440
end
@boun_stress
bou stress @sxx40 @syy40 @szz40 0 0 0 range z 0.0
;Boundary consitions

bou xvel 0.0 yvel 0.0 zvel 0.0 range x -100
bou xvel 0.0 yvel 0.0 zvel 0.0 range x 100
bou xvel 0.0 yvel 0.0 zvel 0.0 range y -100
bou xvel 0.0 yvel 0.0 zvel 0.0 range y 100
bou xvel 0.0 yvel 0.0 zvel 0.0 range z -40
bou xvel 0.0 yvel 0.0 zvel 0.0 range z 40
gravity 0 0 [-gravity_]
;initial equilibrium- mechanical
set flow off mech on
fluid bulk 0.0
hist unbal
;cyc 500
;save mech-equ
;initial equilibrium- fluid
;set flow on mech off
;fluid bulk @fluid_bulk_
;set small
;cyc 500
;save fluid-equ

;set flow on mech on
;fluid bulk @fluid_bulk_
;;set nmech 10
his time
```

```
step 200
save initial


rest initial
reset disp jdisp
;hide range group 'outermodel'
;SET log on
;LIST brick -10 10 -10 10 -10 10 for
;delete range x -1.0 1.0 y -1.0 1.0 z 0, -10

; Function to extrapolate zone stresses to gridpoint extra variable
; for plotting of smooth contours

; Vertex extra 1: maximum compressive stress, s1 (positive compression)
; Vertex extra 2: minimum compressive stress, s3 (positive compression)
===================================================
def plot_stress

  ; first initialize to 0
  local bi = block_head
  loop while bi # 0
    local gpi = b_gp(bi)
    loop while gpi # 0
      gp_extra(gpi,1) = 0.0 ; s1
      gp_extra(gpi,2) = 0.0 ; s3
      gp_extra(gpi,3) = 0.0 ; volume sum
      gpi = gp_next(gpi)
    end_loop
    bi = b_next(bi)
  end_loop

  ; sum stresses and volumes
  bi = block_head
  loop while bi # 0
    local zi = b_zone(bi)
    loop while zi # 0
      local zs1 = -z_sig1(zi)
      local zs3 = -z_sig3(zi)
      local zvol = z_vol(zi)
      loop local zgp (1,4)
        gpi = z_gp(zi,zgp)
        gp_extra(gpi,1) = gp_extra(gpi,1) + zs1*zvol
        gp_extra(gpi,2) = gp_extra(gpi,2) + zs3*zvol
        gp_extra(gpi,3) = gp_extra(gpi,3) + zvol
      end_loop
      zi = z_next(zi)
    end_loop
    bi = b_next(bi)
  end_loop

  ; get weighted average
  bi = block_head
  loop while bi # 0
    gpi = b_gp(bi)
    loop while gpi # 0
      local vol_sum = gp_extra(gpi,3)
      if vol_sum > 0.0
        gp_extra(gpi,1) = gp_extra(gpi,1) / vol_sum
        gp_extra(gpi,2) = gp_extra(gpi,2) / vol_sum
      end_if
      gpi = gp_next(gpi)
    end_loop
    bi = b_next(bi)
  end_loop
end
```

```
===========================================
@plot_stress
plot create plot stress
plot axes
plot gpcontour gp
step 400
seek
save BH

---------------------------------------------
```

Single fracture analysis

```
;elastic
new
poly tunnel rad=1.0 leng=0,10 ratr=9.0 dip=90 dd=0 nr=1 nt=1 nx=1
join on
jset dip 55 dd 90 origin 0,0,-5
jset dip 15 dd 90 origin 0,0,-7
jset dip 15 dd 90 origin 0,0,-3
join on range z -10,-8
join on range z -2,0
gen edge 1.5
;
prop mat=1 dens 2000 bulk 8e9 g 5e9
;change mat 1 cons 2
prop jmat=1 jkn 5e11 jks 2.5e11 jfric 30
;change jmat 1
insitu stress -69e6,-75e6,-83e6 0,0,0 nodisp
insitu pp 27e6 nodisp


bound stress -69e6 0 0 0 0 0 range x -10.0
bound stress -69e6 0 0 0 0 0 range x 10.0
bound stress 0 -75e6 0 0 0 0 range y -10.0
bound stress 0 -75e6 0 0 0 0 range y 10.0
bound stress 0 0 -83e6 0 0 0 range z 0.0
bound zvel 0.0 range z -10.0


hist unbal
hist zdis 0,0,-10

;S3 horizontal

his s3 -10 1.5 -5.0
his s3 -9 1.5 -5.0
his s3 -8 1.5 -5.0
his s3 -7.0 1.5 -5.0
his s3 -6.0 1.5 -5.0
his s3 -5.0 1.5 -5.0
his s3 -4 1.5 -5.0
his s3 -3 1.5 -5.0
his s3 -2 1.5 -5.0
his s3 -1 1.5 -5.0
his s3 -0.5 1.5 -5.0
his s3 -0.25 1.5 -5.0
his s3 0.0 1.5 -5.0
his s3 0.25 1.5 -5.0
his s3 0.5 1.5 -5.0
his s3 1 1.5 -5.0
his s3 2 1.5 -5.0
his s3 3 1.5 -5.0
his s3 4 1.5 -5.0
his s3 5 1.5 -5.0
```

```
his s3 6 1.5 -5.0
his s3 7 1.5 -5.0
his s3 8 1.5 -5.0
his s3 9 1.5 -5.0
his s3 10 1.5 -5.0

;S1horizontal
his s1 -10 1.5 -5.0
his s1 -9 1.5 -5.0
his s1 -8 1.5 -5.0
his s1 -7.0 1.5 -5.0
his s1 -6.0 1.5 -5.0
his s1 -5.0 1.5 -5.0
his s1 -4 1.5 -5.0
his s1 -3 1.5 -5.0
his s1 -2 1.5 -5.0
his s1 -1 1.5 -5.0
his s1 -0.5 1.5 -5.0
his s1 -0.25 1.5 -5.0
his s1 0.0 1.5 -5.0
his s1 0.25 1.5 -5.0
his s1 0.5 1.5 -5.0
his s1 1 1.5 -5.0
his s1 2 1.5 -5.0
his s1 3 1.5 -5.0
his s1 4 1.5 -5.0
his s1 5 1.5 -5.0
his s1 6 1.5 -5.0
his s1 7 1.5 -5.0
his s1 8 1.5 -5.0
his s1 9 1.5 -5.0
his s1 10 1.5 -5.0

;Sdis
his sdis -10 1.5 -5.0
his sdis -9 1.5 -5.0
his sdis -8 1.5 -5.0
his sdis -7.0 1.5 -5.0
his sdis -6.0 1.5 -5.0
his sdis -5.0 1.5 -5.0
his sdis -4 1.5 -5.0
his sdis -3 1.5 -5.0
his sdis -2 1.5 -5.0
his sdis -1 1.5 -5.0
his sdis -0.5 1.5 -5.0
his sdis -0.25 1.5 -5.0
his sdis 0.0 1.5 -5.0
his sdis 0.25 1.5 -5.0
his sdis 0.5 1.5 -5.0
his sdis 1 1.5 -5.0
his sdis 2 1.5 -5.0
his sdis 3 1.5 -5.0
his sdis 4 1.5 -5.0
his sdis 5 1.5 -5.0
his sdis 6 1.5 -5.0
his sdis 7 1.5 -5.0
his sdis 8 1.5 -5.0
his sdis 9 1.5 -5.0
his sdis 10 1.5 -5.0
step 500

reset disp jdisp

save singleFe1
;SET log on
LIST brick -10 10 -10 10 -10 10 for
delete range x -1.0 1.0 y -1.0 1.0 z 0, -10
```

```
def reset_aperture
  local fp = flow_head
  loop while fp # 0
    local fpx = fp_fpx(fp)
    loop while fpx # 0
      fpx_apmech(fpx) = j_ap0
      fpx = fpx_next(fpx)
    end_loop
    fp = fp_next(fp)
  end_loop
end

def bh_setup

 ;maximum aperture
 j_ap_max = 30.0e-4
end

@bh_setup
;.....applying pressure in the borehole
bou stress -28e6 -28e6 -28e6 0.0 0.0 0.0 range cylinder end1 0,0,0 end2 0,0,-10 rad 0,1.05


;
; reset displacements, apertures and time
reset disp jdisp
@reset_aperture
set time 0

; change joint materials to allow for joint opening
prop jmat 1 amax @j_ap_max

; flow only occurs through joints that have failed
set crack_flow on

; setup general fluid properties
fluid bulk 3e6
fluid volmin 1e-3 areamin 0.25
set flow on mech on

; maximum number of mechanical steps per fluid step
;set nmech 5

; inject into center
bound disch 0.001  range cylinder end1 0,0,0 end2 0,0,-10 rad 0,1.0
;his s1 -1.5 -1.5 -5.0

plot clear
plot cut add plane origin (0,0,-10) normal (0,1,0)
plot add jointvector shear shearoffset 0.1 plane on
plot add blockcontour sxz fill on wireframe off
plot add joint colorby material clear addlabel "1" black line width 3
plot set orientation (90,0,0) center (0,0,-10) mag 2.5

step 300
save singleFe2
```

Stress Anisotropy

K 0.5

```
;elastic
new
poly brick -10,10 -10,10 -10,0
```

```
;join on
;jset dip 55 dd 90 origin 0,0,-5
;jset dip 15 dd 90 origin 0,0,-7
;jset dip 15 dd 90 origin 0,0,-3

def fault_id
  F1 = 1
  F2 = 2
end
@fault_id
jset dip 80 dd 90 spac 4 num 8 origin 0 0 0 id @F1

jset dip 45 dd 315 spac 4 num 8 origin 0 0 0 id @F2

;
;join on range z -10,-7
;join on range z 10,-3
gen edge 0.5
;
prop mat=1 dens 2000 bulk 20e9 g 10e9
change mat 1 cons 1

prop jmat=1 jkn 5e11 jks 2.5e11 jfric 28 jcoh 0 jtens 0.0

prop jmat=2 jkn 5e11 jks 2.5e11 jfric 5 jcoh 0 jtens 0.0

change jmat 1 cons 1
change jmat 2 range mint 1 1 ori dip 45 ori dd 315

; K= 0.5 sH 40 Sh 40 sv 80

insitu stress -40e6,-40e6,-80e6 0,0,0 nodisp
insitu pp 27e6 nodisp


bound stress -40e6 0 0 0 0 0 range x -10.0
bound stress -40e6 0 0 0 0 0 range x 10.0
bound stress 0 -40e6 0 0 0 0 range y -10.0
bound stress 0 -40e6 0 0 0 0 range y 10.0
bound stress 0 0 -80e6 0 0 0 range z 0.0
bound zvel 0.0 range z -10.0


hist unbal

;S3 horizontal

his s3 -10 1.5 -5.0
his s3 -9 1.5 -5.0
his s3 -8 1.5 -5.0
his s3 -7.0 1.5 -5.0
his s3 -6.0 1.5 -5.0
his s3 -5.0 1.5 -5.0
his s3 -4 1.5 -5.0
his s3 -3 1.5 -5.0
his s3 -2 1.5 -5.0
his s3 -1 1.5 -5.0
his s3 -0.5 1.5 -5.0
his s3 -0.25 1.5 -5.0
his s3 0.0 1.5 -5.0
his s3 0.25 1.5 -5.0
his s3 0.5 1.5 -5.0
his s3 1 1.5 -5.0
his s3 2 1.5 -5.0
his s3 3 1.5 -5.0
his s3 4 1.5 -5.0
his s3 5 1.5 -5.0
```

```
his s3 6 1.5 -5.0
his s3 7 1.5 -5.0
his s3 8 1.5 -5.0
his s3 9 1.5 -5.0
his s3 10 1.5 -5.0

;S1horizontal
his s1 -10 1.5 -5.0
his s1 -9 1.5 -5.0
his s1 -8 1.5 -5.0
his s1 -7.0 1.5 -5.0
his s1 -6.0 1.5 -5.0
his s1 -5.0 1.5 -5.0
his s1 -4 1.5 -5.0
his s1 -3 1.5 -5.0
his s1 -2 1.5 -5.0
his s1 -1 1.5 -5.0
his s1 -0.5 1.5 -5.0
his s1 -0.25 1.5 -5.0
his s1 0.0 1.5 -5.0
his s1 0.25 1.5 -5.0
his s1 0.5 1.5 -5.0
his s1 1 1.5 -5.0
his s1 2 1.5 -5.0
his s1 3 1.5 -5.0
his s1 4 1.5 -5.0
his s1 5 1.5 -5.0
his s1 6 1.5 -5.0
his s1 7 1.5 -5.0
his s1 8 1.5 -5.0
his s1 9 1.5 -5.0
his s1 10 1.5 -5.0

;Sdis
his sdis -10 1.5 -5.0
his sdis -9 1.5 -5.0
his sdis -8 1.5 -5.0
his sdis -7.0 1.5 -5.0
his sdis -6.0 1.5 -5.0
his sdis -5.0 1.5 -5.0
his sdis -4 1.5 -5.0
his sdis -3 1.5 -5.0
his sdis -2 1.5 -5.0
his sdis -1 1.5 -5.0
his sdis -0.5 1.5 -5.0
his sdis -0.25 1.5 -5.0
his sdis 0.0 1.5 -5.0
his sdis 0.25 1.5 -5.0
his sdis 0.5 1.5 -5.0
his sdis 1 1.5 -5.0
his sdis 2 1.5 -5.0
his sdis 3 1.5 -5.0
his sdis 4 1.5 -5.0
his sdis 5 1.5 -5.0
his sdis 6 1.5 -5.0
his sdis 7 1.5 -5.0
his sdis 8 1.5 -5.0
his sdis 9 1.5 -5.0
his sdis 10 1.5 -5.0


cyc 800

reset disp jdisp

save K0-5
```

```
--------------------------------------

;elastic
new
poly brick -10,10 -10,10 -10,0
;join on
;jset dip 55 dd 90 origin 0,0,-5
;jset dip 15 dd 90 origin 0,0,-7
;jset dip 15 dd 90 origin 0,0,-3

def fault_id
  F1 = 1
  F2 = 2
end
@fault_id
jset dip 80 dd 90 spac 4 num 8 origin 0 0 0 id @F1

jset dip 45 dd 315 spac 4 num 8 origin 0 0 0 id @F2

;
;join on range z -10,-7
;join on range z 10,-3
gen edge 0.5
;
prop mat=1 dens 2000 bulk 20e9 g 10e9
change mat 1 cons 1

prop jmat=1 jkn 5e11 jks 2.5e11 jfric 28 jcoh 0 jtens 0.0

prop jmat=2 jkn 5e11 jks 2.5e11 jfric 5 jcoh 0 jtens 0.0

change jmat 1 cons 1
change jmat 2 range mint 1 1 ori dip 45 ori dd 315

; Isotropic stresses

insitu stress -40e6,-40e6,-40e6 0,0,0 nodisp
insitu pp 27e6 nodisp


bound stress -40e6 0 0 0 0 0 range x -10.0
bound stress -40e6 0 0 0 0 0 range x 10.0
bound stress 0 -40e6 0 0 0 0 range y -10.0
bound stress 0 -40e6 0 0 0 0 range y 10.0
bound stress 0 0 -40e6 0 0 0 range z 0.0
bound zvel 0.0 range z -10.0


hist unbal

;S3 horizontal

his s3 -10 1.5 -5.0
his s3 -9 1.5 -5.0
his s3 -8 1.5 -5.0
his s3 -7.0 1.5 -5.0
his s3 -6.0 1.5 -5.0
his s3 -5.0 1.5 -5.0
his s3 -4 1.5 -5.0
his s3 -3 1.5 -5.0
his s3 -2 1.5 -5.0
his s3 -1 1.5 -5.0
his s3 -0.5 1.5 -5.0
his s3 -0.25 1.5 -5.0
his s3 0.0 1.5 -5.0
his s3 0.25 1.5 -5.0
his s3 0.5 1.5 -5.0
```

```
his s3 1 1.5 -5.0
his s3 2 1.5 -5.0
his s3 3 1.5 -5.0
his s3 4 1.5 -5.0
his s3 5 1.5 -5.0
his s3 6 1.5 -5.0
his s3 7 1.5 -5.0
his s3 8 1.5 -5.0
his s3 9 1.5 -5.0
his s3 10 1.5 -5.0

;S1horizontal
his s1 -10 1.5 -5.0
his s1 -9 1.5 -5.0
his s1 -8 1.5 -5.0
his s1 -7.0 1.5 -5.0
his s1 -6.0 1.5 -5.0
his s1 -5.0 1.5 -5.0
his s1 -4 1.5 -5.0
his s1 -3 1.5 -5.0
his s1 -2 1.5 -5.0
his s1 -1 1.5 -5.0
his s1 -0.5 1.5 -5.0
his s1 -0.25 1.5 -5.0
his s1 0.0 1.5 -5.0
his s1 0.25 1.5 -5.0
his s1 0.5 1.5 -5.0
his s1 1 1.5 -5.0
his s1 2 1.5 -5.0
his s1 3 1.5 -5.0
his s1 4 1.5 -5.0
his s1 5 1.5 -5.0
his s1 6 1.5 -5.0
his s1 7 1.5 -5.0
his s1 8 1.5 -5.0
his s1 9 1.5 -5.0
his s1 10 1.5 -5.0

;Sdis
his sdis -10 1.5 -5.0
his sdis -9 1.5 -5.0
his sdis -8 1.5 -5.0
his sdis -7.0 1.5 -5.0
his sdis -6.0 1.5 -5.0
his sdis -5.0 1.5 -5.0
his sdis -4 1.5 -5.0
his sdis -3 1.5 -5.0
his sdis -2 1.5 -5.0
his sdis -1 1.5 -5.0
his sdis -0.5 1.5 -5.0
his sdis -0.25 1.5 -5.0
his sdis 0.0 1.5 -5.0
his sdis 0.25 1.5 -5.0
his sdis 0.5 1.5 -5.0
his sdis 1 1.5 -5.0
his sdis 2 1.5 -5.0
his sdis 3 1.5 -5.0
his sdis 4 1.5 -5.0
his sdis 5 1.5 -5.0
his sdis 6 1.5 -5.0
his sdis 7 1.5 -5.0
his sdis 8 1.5 -5.0
his sdis 9 1.5 -5.0
his sdis 10 1.5 -5.0


cyc 800
```

```
reset disp jdisp

save K1

-------------------------------
K 2

;elastic
new
poly brick -10,10 -10,10 -10,0
;join on
;jset dip 55 dd 90 origin 0,0,-5
;jset dip 15 dd 90 origin 0,0,-7
;jset dip 15 dd 90 origin 0,0,-3

def fault_id
  F1 = 1
  F2 = 2
end
@fault_id
jset dip 80 dd 90 spac 4 num 8 origin 0 0 0 id @F1

jset dip 45 dd 315 spac 4 num 8 origin 0 0 0 id @F2

;
;join on range z -10,-7
;join on range z 10,-3
gen edge 0.5
;
prop mat=1 dens 2000 bulk 20e9 g 10e9
change mat 1 cons 1

prop jmat=1 jkn 5e11 jks 2.5e11 jfric 28 jcoh 0 jtens 0.0

prop jmat=2 jkn 5e11 jks 2.5e11 jfric 5 jcoh 0 jtens 0.0

change jmat 1 cons 1
change jmat 2 range mint 1 1 ori dip 45 ori dd 315

; K= 2 sH 80 Sh 80 sv 40

insitu stress -80e6,-80e6,-40e6 0,0,0 nodisp
insitu pp 27e6 nodisp


bound stress -80e6 0 0 0 0 0 range x -10.0
bound stress -80e6 0 0 0 0 0 range x 10.0
bound stress 0 -80e6 0 0 0 0 range y -10.0
bound stress 0 -80e6 0 0 0 0 range y 10.0
bound stress 0 0 -40e6 0 0 0 range z 0.0
bound zvel 0.0 range z -10.0


hist unbal

;S3 horizontal

his s3 -10 1.5 -5.0
his s3 -9 1.5 -5.0
his s3 -8 1.5 -5.0
his s3 -7.0 1.5 -5.0
his s3 -6.0 1.5 -5.0
his s3 -5.0 1.5 -5.0
his s3 -4 1.5 -5.0
his s3 -3 1.5 -5.0
his s3 -2 1.5 -5.0
```

```
his s3 -1 1.5 -5.0
his s3 -0.5 1.5 -5.0
his s3 -0.25 1.5 -5.0
his s3 0.0 1.5 -5.0
his s3 0.25 1.5 -5.0
his s3 0.5 1.5 -5.0
his s3 1 1.5 -5.0
his s3 2 1.5 -5.0
his s3 3 1.5 -5.0
his s3 4 1.5 -5.0
his s3 5 1.5 -5.0
his s3 6 1.5 -5.0
his s3 7 1.5 -5.0
his s3 8 1.5 -5.0
his s3 9 1.5 -5.0
his s3 10 1.5 -5.0

;S1horizontal
his s1 -10 1.5 -5.0
his s1 -9 1.5 -5.0
his s1 -8 1.5 -5.0
his s1 -7.0 1.5 -5.0
his s1 -6.0 1.5 -5.0
his s1 -5.0 1.5 -5.0
his s1 -4 1.5 -5.0
his s1 -3 1.5 -5.0
his s1 -2 1.5 -5.0
his s1 -1 1.5 -5.0
his s1 -0.5 1.5 -5.0
his s1 -0.25 1.5 -5.0
his s1 0.0 1.5 -5.0
his s1 0.25 1.5 -5.0
his s1 0.5 1.5 -5.0
his s1 1 1.5 -5.0
his s1 2 1.5 -5.0
his s1 3 1.5 -5.0
his s1 4 1.5 -5.0
his s1 5 1.5 -5.0
his s1 6 1.5 -5.0
his s1 7 1.5 -5.0
his s1 8 1.5 -5.0
his s1 9 1.5 -5.0
his s1 10 1.5 -5.0

;Sdis
his sdis -10 1.5 -5.0
his sdis -9 1.5 -5.0
his sdis -8 1.5 -5.0
his sdis -7.0 1.5 -5.0
his sdis -6.0 1.5 -5.0
his sdis -5.0 1.5 -5.0
his sdis -4 1.5 -5.0
his sdis -3 1.5 -5.0
his sdis -2 1.5 -5.0
his sdis -1 1.5 -5.0
his sdis -0.5 1.5 -5.0
his sdis -0.25 1.5 -5.0
his sdis 0.0 1.5 -5.0
his sdis 0.25 1.5 -5.0
his sdis 0.5 1.5 -5.0
his sdis 1 1.5 -5.0
his sdis 2 1.5 -5.0
his sdis 3 1.5 -5.0
his sdis 4 1.5 -5.0
his sdis 5 1.5 -5.0
his sdis 6 1.5 -5.0
his sdis 7 1.5 -5.0
```

```
his sdis 8 1.5 -5.0
his sdis 9 1.5 -5.0
his sdis 10 1.5 -5.0


cyc 800

reset disp jdisp

save K2

----------------------------------------


K = SH=2Sh

K = 0.5

;elastic
new
poly brick -10,10 -10,10 -10,0
;join on
;jset dip 55 dd 90 origin 0,0,-5
;jset dip 15 dd 90 origin 0,0,-7
;jset dip 15 dd 90 origin 0,0,-3

def fault_id
  F1 = 1
  F2 = 2
end
@fault_id
jset dip 80 dd 90 spac 4 num 8 origin 0 0 0 id @F1

jset dip 45 dd 315 spac 4 num 8 origin 0 0 0 id @F2

;
;join on range z -10,-7
;join on range z 10,-3
gen edge 0.5
;
prop mat=1 dens 2000 bulk 20e9 g 10e9
change mat 1 cons 1

prop jmat=1 jkn 5e11 jks 2.5e11 jfric 28 jcoh 0 jtens 0.0

prop jmat=2 jkn 5e11 jks 2.5e11 jfric 5 jcoh 0 jtens 0.0

change jmat 1 cons 1
change jmat 2 range mint 1 1 ori dip 45 ori dd 315

;SH = 2sh
; K= 0.5 sH 40 Sh 20 sv 80

insitu stress -40e6,-20e6,-80e6 0,0,0 nodisp
insitu pp 27e6 nodisp


bound stress -40e6 0 0 0 0 0 range x -10.0
bound stress -40e6 0 0 0 0 0 range x 10.0
bound stress 0 -20e6 0 0 0 0 range y -10.0
bound stress 0 -20e6 0 0 0 0 range y 10.0
bound stress 0 0 -80e6 0 0 0 range z 0.0
bound zvel 0.0 range z -10.0


hist unbal
```

```
;S3 horizontal

his s3 -10 1.5 -5.0
his s3 -9 1.5 -5.0
his s3 -8 1.5 -5.0
his s3 -7.0 1.5 -5.0
his s3 -6.0 1.5 -5.0
his s3 -5.0 1.5 -5.0
his s3 -4 1.5 -5.0
his s3 -3 1.5 -5.0
his s3 -2 1.5 -5.0
his s3 -1 1.5 -5.0
his s3 -0.5 1.5 -5.0
his s3 -0.25 1.5 -5.0
his s3 0.0 1.5 -5.0
his s3 0.25 1.5 -5.0
his s3 0.5 1.5 -5.0
his s3 1 1.5 -5.0
his s3 2 1.5 -5.0
his s3 3 1.5 -5.0
his s3 4 1.5 -5.0
his s3 5 1.5 -5.0
his s3 6 1.5 -5.0
his s3 7 1.5 -5.0
his s3 8 1.5 -5.0
his s3 9 1.5 -5.0
his s3 10 1.5 -5.0

;S1horizontal
his s1 -10 1.5 -5.0
his s1 -9 1.5 -5.0
his s1 -8 1.5 -5.0
his s1 -7.0 1.5 -5.0
his s1 -6.0 1.5 -5.0
his s1 -5.0 1.5 -5.0
his s1 -4 1.5 -5.0
his s1 -3 1.5 -5.0
his s1 -2 1.5 -5.0
his s1 -1 1.5 -5.0
his s1 -0.5 1.5 -5.0
his s1 -0.25 1.5 -5.0
his s1 0.0 1.5 -5.0
his s1 0.25 1.5 -5.0
his s1 0.5 1.5 -5.0
his s1 1 1.5 -5.0
his s1 2 1.5 -5.0
his s1 3 1.5 -5.0
his s1 4 1.5 -5.0
his s1 5 1.5 -5.0
his s1 6 1.5 -5.0
his s1 7 1.5 -5.0
his s1 8 1.5 -5.0
his s1 9 1.5 -5.0
his s1 10 1.5 -5.0

;Sdis
his sdis -10 1.5 -5.0
his sdis -9 1.5 -5.0
his sdis -8 1.5 -5.0
his sdis -7.0 1.5 -5.0
his sdis -6.0 1.5 -5.0
his sdis -5.0 1.5 -5.0
his sdis -4 1.5 -5.0
his sdis -3 1.5 -5.0
his sdis -2 1.5 -5.0
his sdis -1 1.5 -5.0
his sdis -0.5 1.5 -5.0
```

```
his sdis -0.25 1.5 -5.0
his sdis 0.0 1.5 -5.0
his sdis 0.25 1.5 -5.0
his sdis 0.5 1.5 -5.0
his sdis 1 1.5 -5.0
his sdis 2 1.5 -5.0
his sdis 3 1.5 -5.0
his sdis 4 1.5 -5.0
his sdis 5 1.5 -5.0
his sdis 6 1.5 -5.0
his sdis 7 1.5 -5.0
his sdis 8 1.5 -5.0
his sdis 9 1.5 -5.0
his sdis 10 1.5 -5.0


cyc 800

reset disp jdisp

save K0-5

-------------------------------

K = SH=2Sh

K = 1

;elastic
new
poly brick -10,10 -10,10 -10,0
;join on
;jset dip 55 dd 90 origin 0,0,-5
;jset dip 15 dd 90 origin 0,0,-7
;jset dip 15 dd 90 origin 0,0,-3

def fault_id
  F1 = 1
  F2 = 2
end
@fault_id
jset dip 80 dd 90 spac 4 num 8 origin 0 0 0 id @F1

jset dip 45 dd 315 spac 4 num 8 origin 0 0 0 id @F2

;
;join on range z -10,-7
;join on range z 10,-3
gen edge 0.5
;
prop mat=1 dens 2000 bulk 20e9 g 10e9
change mat 1 cons 1

prop jmat=1 jkn 5e11 jks 2.5e11 jfric 28 jcoh 0 jtens 0.0

prop jmat=2 jkn 5e11 jks 2.5e11 jfric 5 jcoh 0 jtens 0.0

change jmat 1 cons 1
change jmat 2 range mint 1 1 ori dip 45 ori dd 315

;SH = 2sh
; K= 1 sH 40 Sh 20 sv 40

insitu stress -40e6,-20e6,-40e6 0,0,0 nodisp
insitu pp 27e6 nodisp
```

```
bound stress -40e6 0 0 0 0 0 range x -10.0
bound stress -40e6 0 0 0 0 0 range x 10.0
bound stress 0 -20e6 0 0 0 0 range y -10.0
bound stress 0 -20e6 0 0 0 0 range y 10.0
bound stress 0 0 -40e6 0 0 0 range z 0.0
bound zvel 0.0 range z -10.0


hist unbal

;S3 horizontal

his s3 -10 1.5 -5.0
his s3 -9 1.5 -5.0
his s3 -8 1.5 -5.0
his s3 -7.0 1.5 -5.0
his s3 -6.0 1.5 -5.0
his s3 -5.0 1.5 -5.0
his s3 -4 1.5 -5.0
his s3 -3 1.5 -5.0
his s3 -2 1.5 -5.0
his s3 -1 1.5 -5.0
his s3 -0.5 1.5 -5.0
his s3 -0.25 1.5 -5.0
his s3 0.0 1.5 -5.0
his s3 0.25 1.5 -5.0
his s3 0.5 1.5 -5.0
his s3 1 1.5 -5.0
his s3 2 1.5 -5.0
his s3 3 1.5 -5.0
his s3 4 1.5 -5.0
his s3 5 1.5 -5.0
his s3 6 1.5 -5.0
his s3 7 1.5 -5.0
his s3 8 1.5 -5.0
his s3 9 1.5 -5.0
his s3 10 1.5 -5.0

;S1horizontal
his s1 -10 1.5 -5.0
his s1 -9 1.5 -5.0
his s1 -8 1.5 -5.0
his s1 -7.0 1.5 -5.0
his s1 -6.0 1.5 -5.0
his s1 -5.0 1.5 -5.0
his s1 -4 1.5 -5.0
his s1 -3 1.5 -5.0
his s1 -2 1.5 -5.0
his s1 -1 1.5 -5.0
his s1 -0.5 1.5 -5.0
his s1 -0.25 1.5 -5.0
his s1 0.0 1.5 -5.0
his s1 0.25 1.5 -5.0
his s1 0.5 1.5 -5.0
his s1 1 1.5 -5.0
his s1 2 1.5 -5.0
his s1 3 1.5 -5.0
his s1 4 1.5 -5.0
his s1 5 1.5 -5.0
his s1 6 1.5 -5.0
his s1 7 1.5 -5.0
his s1 8 1.5 -5.0
his s1 9 1.5 -5.0
his s1 10 1.5 -5.0

;Sdis
his sdis -10 1.5 -5.0
```

```
his sdis -9 1.5 -5.0
his sdis -8 1.5 -5.0
his sdis -7.0 1.5 -5.0
his sdis -6.0 1.5 -5.0
his sdis -5.0 1.5 -5.0
his sdis -4 1.5 -5.0
his sdis -3 1.5 -5.0
his sdis -2 1.5 -5.0
his sdis -1 1.5 -5.0
his sdis -0.5 1.5 -5.0
his sdis -0.25 1.5 -5.0
his sdis 0.0 1.5 -5.0
his sdis 0.25 1.5 -5.0
his sdis 0.5 1.5 -5.0
his sdis 1 1.5 -5.0
his sdis 2 1.5 -5.0
his sdis 3 1.5 -5.0
his sdis 4 1.5 -5.0
his sdis 5 1.5 -5.0
his sdis 6 1.5 -5.0
his sdis 7 1.5 -5.0
his sdis 8 1.5 -5.0
his sdis 9 1.5 -5.0
his sdis 10 1.5 -5.0


cyc 800

reset disp jdisp

save K1

-------------------------

K = SH=2Sh

K = 2

;elastic
new
poly brick -10,10 -10,10 -10,0
;join on
;jset dip 55 dd 90 origin 0,0,-5
;jset dip 15 dd 90 origin 0,0,-7
;jset dip 15 dd 90 origin 0,0,-3

def fault_id
  F1 = 1
  F2 = 2
end
@fault_id
jset dip 80 dd 90 spac 4 num 8 origin 0 0 0 id @F1

jset dip 45 dd 315 spac 4 num 8 origin 0 0 0 id @F2

;
;join on range z -10,-7
;join on range z 10,-3
gen edge 0.5
;
prop mat=1 dens 2000 bulk 20e9 g 10e9
change mat 1 cons 1

prop jmat=1 jkn 5e11 jks 2.5e11 jfric 28 jcoh 0 jtens 0.0

prop jmat=2 jkn 5e11 jks 2.5e11 jfric 5 jcoh 0 jtens 0.0
```

```
change jmat 1 cons 1
change jmat 2 range mint 1 1 ori dip 45 ori dd 315

;SH = 2sh
; K= 2 sH 80 Sh 40 sv 40

insitu stress -40e6,-20e6,-40e6 0,0,0 nodisp
insitu pp 27e6 nodisp


bound stress -80e6 0 0 0 0 0 range x -10.0
bound stress -80e6 0 0 0 0 0 range x 10.0
bound stress 0 -40e6 0 0 0 0 range y -10.0
bound stress 0 -40e6 0 0 0 0 range y 10.0
bound stress 0 0 -40e6 0 0 0 range z 0.0
bound zvel 0.0 range z -10.0


hist unbal

;S3 horizontal

his s3 -10 1.5 -5.0
his s3 -9 1.5 -5.0
his s3 -8 1.5 -5.0
his s3 -7.0 1.5 -5.0
his s3 -6.0 1.5 -5.0
his s3 -5.0 1.5 -5.0
his s3 -4 1.5 -5.0
his s3 -3 1.5 -5.0
his s3 -2 1.5 -5.0
his s3 -1 1.5 -5.0
his s3 -0.5 1.5 -5.0
his s3 -0.25 1.5 -5.0
his s3 0.0 1.5 -5.0
his s3 0.25 1.5 -5.0
his s3 0.5 1.5 -5.0
his s3 1 1.5 -5.0
his s3 2 1.5 -5.0
his s3 3 1.5 -5.0
his s3 4 1.5 -5.0
his s3 5 1.5 -5.0
his s3 6 1.5 -5.0
his s3 7 1.5 -5.0
his s3 8 1.5 -5.0
his s3 9 1.5 -5.0
his s3 10 1.5 -5.0

;S1horizontal
his s1 -10 1.5 -5.0
his s1 -9 1.5 -5.0
his s1 -8 1.5 -5.0
his s1 -7.0 1.5 -5.0
his s1 -6.0 1.5 -5.0
his s1 -5.0 1.5 -5.0
his s1 -4 1.5 -5.0
his s1 -3 1.5 -5.0
his s1 -2 1.5 -5.0
his s1 -1 1.5 -5.0
his s1 -0.5 1.5 -5.0
his s1 -0.25 1.5 -5.0
his s1 0.0 1.5 -5.0
his s1 0.25 1.5 -5.0
his s1 0.5 1.5 -5.0
his s1 1 1.5 -5.0
his s1 2 1.5 -5.0
his s1 3 1.5 -5.0
```

```
his s1 4 1.5 -5.0
his s1 5 1.5 -5.0
his s1 6 1.5 -5.0
his s1 7 1.5 -5.0
his s1 8 1.5 -5.0
his s1 9 1.5 -5.0
his s1 10 1.5 -5.0

;Sdis
his sdis -10 1.5 -5.0
his sdis -9 1.5 -5.0
his sdis -8 1.5 -5.0
his sdis -7.0 1.5 -5.0
his sdis -6.0 1.5 -5.0
his sdis -5.0 1.5 -5.0
his sdis -4 1.5 -5.0
his sdis -3 1.5 -5.0
his sdis -2 1.5 -5.0
his sdis -1 1.5 -5.0
his sdis -0.5 1.5 -5.0
his sdis -0.25 1.5 -5.0
his sdis 0.0 1.5 -5.0
his sdis 0.25 1.5 -5.0
his sdis 0.5 1.5 -5.0
his sdis 1 1.5 -5.0
his sdis 2 1.5 -5.0
his sdis 3 1.5 -5.0
his sdis 4 1.5 -5.0
his sdis 5 1.5 -5.0
his sdis 6 1.5 -5.0
his sdis 7 1.5 -5.0
his sdis 8 1.5 -5.0
his sdis 9 1.5 -5.0
his sdis 10 1.5 -5.0


cyc 800

reset disp jdisp

save K2

---------------------------
```

Strength Anisotropy

Friction

F12C0

```
;elastic
new
poly brick -10,10 -10,10 -10,0
;join on
;jset dip 55 dd 90 origin 0,0,-5
;jset dip 15 dd 90 origin 0,0,-7
;jset dip 15 dd 90 origin 0,0,-3

def fault_id
  F1 = 1
  F2 = 2
end
@fault_id
jset dip 80 dd 90 spac 4 num 8 origin 0 0 0 id @F1

jset dip 45 dd 315 spac 4 num 8 origin 0 0 0 id @F2
```

```
;
;join on range z -10,-7
;join on range z 10,-3
gen edge 0.5
;
prop mat=1 dens 2000 bulk 20e9 g 10e9
change mat 1 cons 1

prop jmat=1 jkn 5e11 jks 2.5e11 jfric 32 jcoh 0 jtens 0.0

prop jmat=2 jkn 5e11 jks 2.5e11 jfric 12 jcoh 0 jtens 0.0

change jmat 1 cons 1
change jmat 2 range mint 1 1 ori dip 45 ori dd 315

insitu stress -50e6,-55e6,-83e6 0,0,0 nodisp
insitu pp 27e6 nodisp


bound stress -50e6 0 0 0 0 0 range x -10.0
bound stress -50e6 0 0 0 0 0 range x 10.0
bound stress 0 -55e6 0 0 0 0 range y -10.0
bound stress 0 -55e6 0 0 0 0 range y 10.0
bound stress 0 0 -83e6 0 0 0 range z 0.0
bound zvel 0.0 range z -10.0


hist unbal

;S3 horizontal

his s3 -10 1.5 -5.0
his s3 -9 1.5 -5.0
his s3 -8 1.5 -5.0
his s3 -7.0 1.5 -5.0
his s3 -6.0 1.5 -5.0
his s3 -5.0 1.5 -5.0
his s3 -4 1.5 -5.0
his s3 -3 1.5 -5.0
his s3 -2 1.5 -5.0
his s3 -1 1.5 -5.0
his s3 -0.5 1.5 -5.0
his s3 -0.25 1.5 -5.0
his s3 0.0 1.5 -5.0
his s3 0.25 1.5 -5.0
his s3 0.5 1.5 -5.0
his s3 1 1.5 -5.0
his s3 2 1.5 -5.0
his s3 3 1.5 -5.0
his s3 4 1.5 -5.0
his s3 5 1.5 -5.0
his s3 6 1.5 -5.0
his s3 7 1.5 -5.0
his s3 8 1.5 -5.0
his s3 9 1.5 -5.0
his s3 10 1.5 -5.0

;S1horizontal
his s1 -10 1.5 -5.0
his s1 -9 1.5 -5.0
his s1 -8 1.5 -5.0
his s1 -7.0 1.5 -5.0
his s1 -6.0 1.5 -5.0
his s1 -5.0 1.5 -5.0
his s1 -4 1.5 -5.0
his s1 -3 1.5 -5.0
his s1 -2 1.5 -5.0
```

```
his s1 -1 1.5 -5.0
his s1 -0.5 1.5 -5.0
his s1 -0.25 1.5 -5.0
his s1 0.0 1.5 -5.0
his s1 0.25 1.5 -5.0
his s1 0.5 1.5 -5.0
his s1 1 1.5 -5.0
his s1 2 1.5 -5.0
his s1 3 1.5 -5.0
his s1 4 1.5 -5.0
his s1 5 1.5 -5.0
his s1 6 1.5 -5.0
his s1 7 1.5 -5.0
his s1 8 1.5 -5.0
his s1 9 1.5 -5.0
his s1 10 1.5 -5.0

;Sdis
his sdis -10 1.5 -5.0
his sdis -9 1.5 -5.0
his sdis -8 1.5 -5.0
his sdis -7.0 1.5 -5.0
his sdis -6.0 1.5 -5.0
his sdis -5.0 1.5 -5.0
his sdis -4 1.5 -5.0
his sdis -3 1.5 -5.0
his sdis -2 1.5 -5.0
his sdis -1 1.5 -5.0
his sdis -0.5 1.5 -5.0
his sdis -0.25 1.5 -5.0
his sdis 0.0 1.5 -5.0
his sdis 0.25 1.5 -5.0
his sdis 0.5 1.5 -5.0
his sdis 1 1.5 -5.0
his sdis 2 1.5 -5.0
his sdis 3 1.5 -5.0
his sdis 4 1.5 -5.0
his sdis 5 1.5 -5.0
his sdis 6 1.5 -5.0
his sdis 7 1.5 -5.0
his sdis 8 1.5 -5.0
his sdis 9 1.5 -5.0
his sdis 10 1.5 -5.0


cyc 800

reset disp jdisp

save F12C0-1

---------------------------------

F22 C0

;elastic
new
poly brick -10,10 -10,10 -10,0
;join on
;jset dip 55 dd 90 origin 0,0,-5
;jset dip 15 dd 90 origin 0,0,-7
;jset dip 15 dd 90 origin 0,0,-3

def fault_id
  F1 = 1
  F2 = 2
end
```

```
@fault_id
jset dip 80 dd 90 spac 4 num 8 origin 0 0 0 id @F1

jset dip 45 dd 315 spac 4 num 8 origin 0 0 0 id @F2

;
;join on range z -10,-7
;join on range z 10,-3
gen edge 0.5
;
prop mat=1 dens 2000 bulk 20e9 g 10e9
change mat 1 cons 1

prop jmat=1 jkn 5e11 jks 2.5e11 jfric 32 jcoh 0 jtens 0.0

prop jmat=2 jkn 5e11 jks 2.5e11 jfric 22 jcoh 0 jtens 0.0

change jmat 1 cons 1
change jmat 2 range mint 1 1 ori dip 45 ori dd 315

insitu stress -50e6,-55e6,-83e6 0,0,0 nodisp
insitu pp 27e6 nodisp


bound stress -50e6 0 0 0 0 0 range x -10.0
bound stress -50e6 0 0 0 0 0 range x 10.0
bound stress 0 -55e6 0 0 0 0 range y -10.0
bound stress 0 -55e6 0 0 0 0 range y 10.0
bound stress 0 0 -83e6 0 0 0 range z 0.0
bound zvel 0.0 range z -10.0


hist unbal

;S3 horizontal

his s3 -10 1.5 -5.0
his s3 -9 1.5 -5.0
his s3 -8 1.5 -5.0
his s3 -7.0 1.5 -5.0
his s3 -6.0 1.5 -5.0
his s3 -5.0 1.5 -5.0
his s3 -4 1.5 -5.0
his s3 -3 1.5 -5.0
his s3 -2 1.5 -5.0
his s3 -1 1.5 -5.0
his s3 -0.5 1.5 -5.0
his s3 -0.25 1.5 -5.0
his s3 0.0 1.5 -5.0
his s3 0.25 1.5 -5.0
his s3 0.5 1.5 -5.0
his s3 1 1.5 -5.0
his s3 2 1.5 -5.0
his s3 3 1.5 -5.0
his s3 4 1.5 -5.0
his s3 5 1.5 -5.0
his s3 6 1.5 -5.0
his s3 7 1.5 -5.0
his s3 8 1.5 -5.0
his s3 9 1.5 -5.0
his s3 10 1.5 -5.0

;S1horizontal
his s1 -10 1.5 -5.0
his s1 -9 1.5 -5.0
his s1 -8 1.5 -5.0
his s1 -7.0 1.5 -5.0
```

```
his s1 -6.0 1.5 -5.0
his s1 -5.0 1.5 -5.0
his s1 -4 1.5 -5.0
his s1 -3 1.5 -5.0
his s1 -2 1.5 -5.0
his s1 -1 1.5 -5.0
his s1 -0.5 1.5 -5.0
his s1 -0.25 1.5 -5.0
his s1 0.0 1.5 -5.0
his s1 0.25 1.5 -5.0
his s1 0.5 1.5 -5.0
his s1 1 1.5 -5.0
his s1 2 1.5 -5.0
his s1 3 1.5 -5.0
his s1 4 1.5 -5.0
his s1 5 1.5 -5.0
his s1 6 1.5 -5.0
his s1 7 1.5 -5.0
his s1 8 1.5 -5.0
his s1 9 1.5 -5.0
his s1 10 1.5 -5.0

;Sdis
his sdis -10 1.5 -5.0
his sdis -9 1.5 -5.0
his sdis -8 1.5 -5.0
his sdis -7.0 1.5 -5.0
his sdis -6.0 1.5 -5.0
his sdis -5.0 1.5 -5.0
his sdis -4 1.5 -5.0
his sdis -3 1.5 -5.0
his sdis -2 1.5 -5.0
his sdis -1 1.5 -5.0
his sdis -0.5 1.5 -5.0
his sdis -0.25 1.5 -5.0
his sdis 0.0 1.5 -5.0
his sdis 0.25 1.5 -5.0
his sdis 0.5 1.5 -5.0
his sdis 1 1.5 -5.0
his sdis 2 1.5 -5.0
his sdis 3 1.5 -5.0
his sdis 4 1.5 -5.0
his sdis 5 1.5 -5.0
his sdis 6 1.5 -5.0
his sdis 7 1.5 -5.0
his sdis 8 1.5 -5.0
his sdis 9 1.5 -5.0
his sdis 10 1.5 -5.0


cyc 800

reset disp jdisp

save F22C0-1
---------------------------

F323 C0

;elastic
new
poly brick -10,10 -10,10 -10,0
;join on
;jset dip 55 dd 90 origin 0,0,-5
;jset dip 15 dd 90 origin 0,0,-7
;jset dip 15 dd 90 origin 0,0,-3
```

```
def fault_id
  F1 = 1
  F2 = 2
end
@fault_id
jset dip 80 dd 90 spac 4 num 8 origin 0 0 0 id @F1

jset dip 45 dd 315 spac 4 num 8 origin 0 0 0 id @F2

;
;join on range z -10,-7
;join on range z 10,-3
gen edge 0.5
;
prop mat=1 dens 2000 bulk 20e9 g 10e9
change mat 1 cons 1

prop jmat=1 jkn 5e11 jks 2.5e11 jfric 32 jcoh 0 jtens 0.0

prop jmat=2 jkn 5e11 jks 2.5e11 jfric 32 jcoh 0 jtens 0.0

change jmat 1 cons 1
change jmat 2 range mint 1 1 ori dip 45 ori dd 315

insitu stress -50e6,-55e6,-83e6 0,0,0 nodisp
insitu pp 27e6 nodisp


bound stress -50e6 0 0 0 0 0 range x -10.0
bound stress -50e6 0 0 0 0 0 range x 10.0
bound stress 0 -55e6 0 0 0 0 range y -10.0
bound stress 0 -55e6 0 0 0 0 range y 10.0
bound stress 0 0 -83e6 0 0 0 range z 0.0
bound zvel 0.0 range z -10.0


hist unbal

;S3 horizontal

his s3 -10 1.5 -5.0
his s3 -9 1.5 -5.0
his s3 -8 1.5 -5.0
his s3 -7.0 1.5 -5.0
his s3 -6.0 1.5 -5.0
his s3 -5.0 1.5 -5.0
his s3 -4 1.5 -5.0
his s3 -3 1.5 -5.0
his s3 -2 1.5 -5.0
his s3 -1 1.5 -5.0
his s3 -0.5 1.5 -5.0
his s3 -0.25 1.5 -5.0
his s3 0.0 1.5 -5.0
his s3 0.25 1.5 -5.0
his s3 0.5 1.5 -5.0
his s3 1 1.5 -5.0
his s3 2 1.5 -5.0
his s3 3 1.5 -5.0
his s3 4 1.5 -5.0
his s3 5 1.5 -5.0
his s3 6 1.5 -5.0
his s3 7 1.5 -5.0
his s3 8 1.5 -5.0
his s3 9 1.5 -5.0
his s3 10 1.5 -5.0

;S1horizontal
```

```
his s1 -10 1.5 -5.0
his s1 -9 1.5 -5.0
his s1 -8 1.5 -5.0
his s1 -7.0 1.5 -5.0
his s1 -6.0 1.5 -5.0
his s1 -5.0 1.5 -5.0
his s1 -4 1.5 -5.0
his s1 -3 1.5 -5.0
his s1 -2 1.5 -5.0
his s1 -1 1.5 -5.0
his s1 -0.5 1.5 -5.0
his s1 -0.25 1.5 -5.0
his s1 0.0 1.5 -5.0
his s1 0.25 1.5 -5.0
his s1 0.5 1.5 -5.0
his s1 1 1.5 -5.0
his s1 2 1.5 -5.0
his s1 3 1.5 -5.0
his s1 4 1.5 -5.0
his s1 5 1.5 -5.0
his s1 6 1.5 -5.0
his s1 7 1.5 -5.0
his s1 8 1.5 -5.0
his s1 9 1.5 -5.0
his s1 10 1.5 -5.0

;Sdis
his sdis -10 1.5 -5.0
his sdis -9 1.5 -5.0
his sdis -8 1.5 -5.0
his sdis -7.0 1.5 -5.0
his sdis -6.0 1.5 -5.0
his sdis -5.0 1.5 -5.0
his sdis -4 1.5 -5.0
his sdis -3 1.5 -5.0
his sdis -2 1.5 -5.0
his sdis -1 1.5 -5.0
his sdis -0.5 1.5 -5.0
his sdis -0.25 1.5 -5.0
his sdis 0.0 1.5 -5.0
his sdis 0.25 1.5 -5.0
his sdis 0.5 1.5 -5.0
his sdis 1 1.5 -5.0
his sdis 2 1.5 -5.0
his sdis 3 1.5 -5.0
his sdis 4 1.5 -5.0
his sdis 5 1.5 -5.0
his sdis 6 1.5 -5.0
his sdis 7 1.5 -5.0
his sdis 8 1.5 -5.0
his sdis 9 1.5 -5.0
his sdis 10 1.5 -5.0


cyc 800

reset disp jdisp

save F32C0-1

---------------------------------------------

F42 C0

;elastic
new
poly brick -10,10 -10,10 -10,0
```

```
;join on
;jset dip 55 dd 90 origin 0,0,-5
;jset dip 15 dd 90 origin 0,0,-7
;jset dip 15 dd 90 origin 0,0,-3

def fault_id
  F1 = 1
  F2 = 2
end
@fault_id
jset dip 80 dd 90 spac 4 num 8 origin 0 0 0 id @F1

jset dip 45 dd 315 spac 4 num 8 origin 0 0 0 id @F2

;
;join on range z -10,-7
;join on range z 10,-3
gen edge 0.5
;
prop mat=1 dens 2000 bulk 20e9 g 10e9
change mat 1 cons 1

prop jmat=1 jkn 5e11 jks 2.5e11 jfric 32 jcoh 0 jtens 0.0

prop jmat=2 jkn 5e11 jks 2.5e11 jfric 42 jcoh 0 jtens 0.0

change jmat 1 cons 1
change jmat 2 range mint 1 1 ori dip 45 ori dd 315

insitu stress -50e6,-55e6,-83e6 0,0,0 nodisp
insitu pp 27e6 nodisp


bound stress -50e6 0 0 0 0 0 range x -10.0
bound stress -50e6 0 0 0 0 0 range x 10.0
bound stress 0 -55e6 0 0 0 0 range y -10.0
bound stress 0 -55e6 0 0 0 0 range y 10.0
bound stress 0 0 -83e6 0 0 0 range z 0.0
bound zvel 0.0 range z -10.0


hist unbal

;S3 horizontal

his s3 -10 1.5 -5.0
his s3 -9 1.5 -5.0
his s3 -8 1.5 -5.0
his s3 -7.0 1.5 -5.0
his s3 -6.0 1.5 -5.0
his s3 -5.0 1.5 -5.0
his s3 -4 1.5 -5.0
his s3 -3 1.5 -5.0
his s3 -2 1.5 -5.0
his s3 -1 1.5 -5.0
his s3 -0.5 1.5 -5.0
his s3 -0.25 1.5 -5.0
his s3 0.0 1.5 -5.0
his s3 0.25 1.5 -5.0
his s3 0.5 1.5 -5.0
his s3 1 1.5 -5.0
his s3 2 1.5 -5.0
his s3 3 1.5 -5.0
his s3 4 1.5 -5.0
his s3 5 1.5 -5.0
his s3 6 1.5 -5.0
his s3 7 1.5 -5.0
```

```
his s3 8 1.5 -5.0
his s3 9 1.5 -5.0
his s3 10 1.5 -5.0

;S1horizontal
his s1 -10 1.5 -5.0
his s1 -9 1.5 -5.0
his s1 -8 1.5 -5.0
his s1 -7.0 1.5 -5.0
his s1 -6.0 1.5 -5.0
his s1 -5.0 1.5 -5.0
his s1 -4 1.5 -5.0
his s1 -3 1.5 -5.0
his s1 -2 1.5 -5.0
his s1 -1 1.5 -5.0
his s1 -0.5 1.5 -5.0
his s1 -0.25 1.5 -5.0
his s1 0.0 1.5 -5.0
his s1 0.25 1.5 -5.0
his s1 0.5 1.5 -5.0
his s1 1 1.5 -5.0
his s1 2 1.5 -5.0
his s1 3 1.5 -5.0
his s1 4 1.5 -5.0
his s1 5 1.5 -5.0
his s1 6 1.5 -5.0
his s1 7 1.5 -5.0
his s1 8 1.5 -5.0
his s1 9 1.5 -5.0
his s1 10 1.5 -5.0

;Sdis
his sdis -10 1.5 -5.0
his sdis -9 1.5 -5.0
his sdis -8 1.5 -5.0
his sdis -7.0 1.5 -5.0
his sdis -6.0 1.5 -5.0
his sdis -5.0 1.5 -5.0
his sdis -4 1.5 -5.0
his sdis -3 1.5 -5.0
his sdis -2 1.5 -5.0
his sdis -1 1.5 -5.0
his sdis -0.5 1.5 -5.0
his sdis -0.25 1.5 -5.0
his sdis 0.0 1.5 -5.0
his sdis 0.25 1.5 -5.0
his sdis 0.5 1.5 -5.0
his sdis 1 1.5 -5.0
his sdis 2 1.5 -5.0
his sdis 3 1.5 -5.0
his sdis 4 1.5 -5.0
his sdis 5 1.5 -5.0
his sdis 6 1.5 -5.0
his sdis 7 1.5 -5.0
his sdis 8 1.5 -5.0
his sdis 9 1.5 -5.0
his sdis 10 1.5 -5.0


cyc 800

reset disp jdisp

save F42C0-1
------------------------------
```

F52 C0

```
;elastic
new
poly brick -10,10 -10,10 -10,0
;join on
;jset dip 55 dd 90 origin 0,0,-5
;jset dip 15 dd 90 origin 0,0,-7
;jset dip 15 dd 90 origin 0,0,-3

def fault_id
  F1 = 1
  F2 = 2
end
@fault_id
jset dip 80 dd 90 spac 4 num 8 origin 0 0 0 id @F1

jset dip 45 dd 315 spac 4 num 8 origin 0 0 0 id @F2

;
;join on range z -10,-7
;join on range z 10,-3
gen edge 0.5
;
prop mat=1 dens 2000 bulk 20e9 g 10e9
change mat 1 cons 1

prop jmat=1 jkn 5e11 jks 2.5e11 jfric 32 jcoh 0 jtens 0.0

prop jmat=2 jkn 5e11 jks 2.5e11 jfric 52 jcoh 0 jtens 0.0

change jmat 1 cons 1
change jmat 2 range mint 1 1 ori dip 45 ori dd 315

insitu stress -50e6,-55e6,-83e6 0,0,0 nodisp
insitu pp 27e6 nodisp


bound stress -50e6 0 0 0 0 0 range x -10.0
bound stress -50e6 0 0 0 0 0 range x 10.0
bound stress 0 -55e6 0 0 0 0 range y -10.0
bound stress 0 -55e6 0 0 0 0 range y 10.0
bound stress 0 0 -83e6 0 0 0 range z 0.0
bound zvel 0.0 range z -10.0


hist unbal

;S3 horizontal

his s3 -10 1.5 -5.0
his s3 -9 1.5 -5.0
his s3 -8 1.5 -5.0
his s3 -7.0 1.5 -5.0
his s3 -6.0 1.5 -5.0
his s3 -5.0 1.5 -5.0
his s3 -4 1.5 -5.0
his s3 -3 1.5 -5.0
his s3 -2 1.5 -5.0
his s3 -1 1.5 -5.0
his s3 -0.5 1.5 -5.0
his s3 -0.25 1.5 -5.0
his s3 0.0 1.5 -5.0
his s3 0.25 1.5 -5.0
his s3 0.5 1.5 -5.0
his s3 1 1.5 -5.0
his s3 2 1.5 -5.0
his s3 3 1.5 -5.0
```

```
his s3 4 1.5 -5.0
his s3 5 1.5 -5.0
his s3 6 1.5 -5.0
his s3 7 1.5 -5.0
his s3 8 1.5 -5.0
his s3 9 1.5 -5.0
his s3 10 1.5 -5.0

;S1horizontal
his s1 -10 1.5 -5.0
his s1 -9 1.5 -5.0
his s1 -8 1.5 -5.0
his s1 -7.0 1.5 -5.0
his s1 -6.0 1.5 -5.0
his s1 -5.0 1.5 -5.0
his s1 -4 1.5 -5.0
his s1 -3 1.5 -5.0
his s1 -2 1.5 -5.0
his s1 -1 1.5 -5.0
his s1 -0.5 1.5 -5.0
his s1 -0.25 1.5 -5.0
his s1 0.0 1.5 -5.0
his s1 0.25 1.5 -5.0
his s1 0.5 1.5 -5.0
his s1 1 1.5 -5.0
his s1 2 1.5 -5.0
his s1 3 1.5 -5.0
his s1 4 1.5 -5.0
his s1 5 1.5 -5.0
his s1 6 1.5 -5.0
his s1 7 1.5 -5.0
his s1 8 1.5 -5.0
his s1 9 1.5 -5.0
his s1 10 1.5 -5.0

;Sdis
his sdis -10 1.5 -5.0
his sdis -9 1.5 -5.0
his sdis -8 1.5 -5.0
his sdis -7.0 1.5 -5.0
his sdis -6.0 1.5 -5.0
his sdis -5.0 1.5 -5.0
his sdis -4 1.5 -5.0
his sdis -3 1.5 -5.0
his sdis -2 1.5 -5.0
his sdis -1 1.5 -5.0
his sdis -0.5 1.5 -5.0
his sdis -0.25 1.5 -5.0
his sdis 0.0 1.5 -5.0
his sdis 0.25 1.5 -5.0
his sdis 0.5 1.5 -5.0
his sdis 1 1.5 -5.0
his sdis 2 1.5 -5.0
his sdis 3 1.5 -5.0
his sdis 4 1.5 -5.0
his sdis 5 1.5 -5.0
his sdis 6 1.5 -5.0
his sdis 7 1.5 -5.0
his sdis 8 1.5 -5.0
his sdis 9 1.5 -5.0
his sdis 10 1.5 -5.0


cyc 800

reset disp jdisp
```

```
save F52C0-1
-------------------------
```

Cohesion

C0 F32

```
;elastic
new
poly brick -10,10 -10,10 -10,0
;join on
;jset dip 55 dd 90 origin 0,0,-5
;jset dip 15 dd 90 origin 0,0,-7
;jset dip 15 dd 90 origin 0,0,-3

def fault_id
  F1 = 1
  F2 = 2
end
@fault_id
jset dip 80 dd 90 spac 4 num 8 origin 0 0 0 id @F1

jset dip 45 dd 315 spac 4 num 8 origin 0 0 0 id @F2

;
;join on range z -10,-7
;join on range z 10,-3
gen edge 0.5
;
prop mat=1 dens 2000 bulk 20e9 g 10e9
change mat 1 cons 1

prop jmat=1 jkn 5e11 jks 2.5e11 jfric 32 jcoh 0 jtens 0.0

prop jmat=2 jkn 5e11 jks 2.5e11 jfric 32 jcoh 0 jtens 0.0

change jmat 1 cons 1
change jmat 2 range mint 1 1 ori dip 45 ori dd 315

insitu stress -50e6,-55e6,-83e6 0,0,0 nodisp
insitu pp 27e6 nodisp


bound stress -50e6 0 0 0 0 0 range x -10.0
bound stress -50e6 0 0 0 0 0 range x 10.0
bound stress 0 -55e6 0 0 0 0 range y -10.0
bound stress 0 -55e6 0 0 0 0 range y 10.0
bound stress 0 0 -83e6 0 0 0 range z 0.0
bound zvel 0.0 range z -10.0


hist unbal

;S3 horizontal

his s3 -10 1.5 -5.0
his s3 -9 1.5 -5.0
his s3 -8 1.5 -5.0
his s3 -7.0 1.5 -5.0
his s3 -6.0 1.5 -5.0
his s3 -5.0 1.5 -5.0
his s3 -4 1.5 -5.0
his s3 -3 1.5 -5.0
his s3 -2 1.5 -5.0
his s3 -1 1.5 -5.0
his s3 -0.5 1.5 -5.0
his s3 -0.25 1.5 -5.0
```

```
his s3 0.0 1.5 -5.0
his s3 0.25 1.5 -5.0
his s3 0.5 1.5 -5.0
his s3 1 1.5 -5.0
his s3 2 1.5 -5.0
his s3 3 1.5 -5.0
his s3 4 1.5 -5.0
his s3 5 1.5 -5.0
his s3 6 1.5 -5.0
his s3 7 1.5 -5.0
his s3 8 1.5 -5.0
his s3 9 1.5 -5.0
his s3 10 1.5 -5.0

;S1horizontal
his s1 -10 1.5 -5.0
his s1 -9 1.5 -5.0
his s1 -8 1.5 -5.0
his s1 -7.0 1.5 -5.0
his s1 -6.0 1.5 -5.0
his s1 -5.0 1.5 -5.0
his s1 -4 1.5 -5.0
his s1 -3 1.5 -5.0
his s1 -2 1.5 -5.0
his s1 -1 1.5 -5.0
his s1 -0.5 1.5 -5.0
his s1 -0.25 1.5 -5.0
his s1 0.0 1.5 -5.0
his s1 0.25 1.5 -5.0
his s1 0.5 1.5 -5.0
his s1 1 1.5 -5.0
his s1 2 1.5 -5.0
his s1 3 1.5 -5.0
his s1 4 1.5 -5.0
his s1 5 1.5 -5.0
his s1 6 1.5 -5.0
his s1 7 1.5 -5.0
his s1 8 1.5 -5.0
his s1 9 1.5 -5.0
his s1 10 1.5 -5.0

;Sdis
his sdis -10 1.5 -5.0
his sdis -9 1.5 -5.0
his sdis -8 1.5 -5.0
his sdis -7.0 1.5 -5.0
his sdis -6.0 1.5 -5.0
his sdis -5.0 1.5 -5.0
his sdis -4 1.5 -5.0
his sdis -3 1.5 -5.0
his sdis -2 1.5 -5.0
his sdis -1 1.5 -5.0
his sdis -0.5 1.5 -5.0
his sdis -0.25 1.5 -5.0
his sdis 0.0 1.5 -5.0
his sdis 0.25 1.5 -5.0
his sdis 0.5 1.5 -5.0
his sdis 1 1.5 -5.0
his sdis 2 1.5 -5.0
his sdis 3 1.5 -5.0
his sdis 4 1.5 -5.0
his sdis 5 1.5 -5.0
his sdis 6 1.5 -5.0
his sdis 7 1.5 -5.0
his sdis 8 1.5 -5.0
his sdis 9 1.5 -5.0
his sdis 10 1.5 -5.0
```

```
cyc 800

reset disp jdisp

save F32C0-1
----------------------

C 0.5 F32

;elastic
new
poly brick -10,10 -10,10 -10,0
;join on
;jset dip 55 dd 90 origin 0,0,-5
;jset dip 15 dd 90 origin 0,0,-7
;jset dip 15 dd 90 origin 0,0,-3

def fault_id
  F1 = 1
  F2 = 2
end
@fault_id
jset dip 80 dd 90 spac 4 num 8 origin 0 0 0 id @F1

jset dip 45 dd 315 spac 4 num 8 origin 0 0 0 id @F2

;
;join on range z -10,-7
;join on range z 10,-3
gen edge 0.5
;
prop mat=1 dens 2000 bulk 20e9 g 10e9
change mat 1 cons 1

prop jmat=1 jkn 5e11 jks 2.5e11 jfric 32 jcoh 0 jtens 0.0

prop jmat=2 jkn 5e11 jks 2.5e11 jfric 32 jcoh 0.5e6 jtens 0.0

change jmat 1 cons 1
change jmat 2 range mint 1 1 ori dip 45 ori dd 315

insitu stress -50e6,-55e6,-83e6 0,0,0 nodisp
insitu pp 27e6 nodisp


bound stress -50e6 0 0 0 0 0 range x -10.0
bound stress -50e6 0 0 0 0 0 range x 10.0
bound stress 0 -55e6 0 0 0 0 range y -10.0
bound stress 0 -55e6 0 0 0 0 range y 10.0
bound stress 0 0 -83e6 0 0 0 range z 0.0
bound zvel 0.0 range z -10.0


hist unbal

;S3 horizontal

his s3 -10 1.5 -5.0
his s3 -9 1.5 -5.0
his s3 -8 1.5 -5.0
his s3 -7.0 1.5 -5.0
his s3 -6.0 1.5 -5.0
his s3 -5.0 1.5 -5.0
his s3 -4 1.5 -5.0
his s3 -3 1.5 -5.0
```

```
his s3 -2 1.5 -5.0
his s3 -1 1.5 -5.0
his s3 -0.5 1.5 -5.0
his s3 -0.25 1.5 -5.0
his s3 0.0 1.5 -5.0
his s3 0.25 1.5 -5.0
his s3 0.5 1.5 -5.0
his s3 1 1.5 -5.0
his s3 2 1.5 -5.0
his s3 3 1.5 -5.0
his s3 4 1.5 -5.0
his s3 5 1.5 -5.0
his s3 6 1.5 -5.0
his s3 7 1.5 -5.0
his s3 8 1.5 -5.0
his s3 9 1.5 -5.0
his s3 10 1.5 -5.0

;S1horizontal
his s1 -10 1.5 -5.0
his s1 -9 1.5 -5.0
his s1 -8 1.5 -5.0
his s1 -7.0 1.5 -5.0
his s1 -6.0 1.5 -5.0
his s1 -5.0 1.5 -5.0
his s1 -4 1.5 -5.0
his s1 -3 1.5 -5.0
his s1 -2 1.5 -5.0
his s1 -1 1.5 -5.0
his s1 -0.5 1.5 -5.0
his s1 -0.25 1.5 -5.0
his s1 0.0 1.5 -5.0
his s1 0.25 1.5 -5.0
his s1 0.5 1.5 -5.0
his s1 1 1.5 -5.0
his s1 2 1.5 -5.0
his s1 3 1.5 -5.0
his s1 4 1.5 -5.0
his s1 5 1.5 -5.0
his s1 6 1.5 -5.0
his s1 7 1.5 -5.0
his s1 8 1.5 -5.0
his s1 9 1.5 -5.0
his s1 10 1.5 -5.0

;Sdis
his sdis -10 1.5 -5.0
his sdis -9 1.5 -5.0
his sdis -8 1.5 -5.0
his sdis -7.0 1.5 -5.0
his sdis -6.0 1.5 -5.0
his sdis -5.0 1.5 -5.0
his sdis -4 1.5 -5.0
his sdis -3 1.5 -5.0
his sdis -2 1.5 -5.0
his sdis -1 1.5 -5.0
his sdis -0.5 1.5 -5.0
his sdis -0.25 1.5 -5.0
his sdis 0.0 1.5 -5.0
his sdis 0.25 1.5 -5.0
his sdis 0.5 1.5 -5.0
his sdis 1 1.5 -5.0
his sdis 2 1.5 -5.0
his sdis 3 1.5 -5.0
his sdis 4 1.5 -5.0
his sdis 5 1.5 -5.0
his sdis 6 1.5 -5.0
```

```
his sdis 7 1.5 -5.0
his sdis 8 1.5 -5.0
his sdis 9 1.5 -5.0
his sdis 10 1.5 -5.0


cyc 800

reset disp jdisp

save F32C0-5

------------------------------
```

F32 C1

```
;elastic
new
poly brick -10,10 -10,10 -10,0
;join on
;jset dip 55 dd 90 origin 0,0,-5
;jset dip 15 dd 90 origin 0,0,-7
;jset dip 15 dd 90 origin 0,0,-3

def fault_id
  F1 = 1
  F2 = 2
end
@fault_id
jset dip 80 dd 90 spac 4 num 8 origin 0 0 0 id @F1

jset dip 45 dd 315 spac 4 num 8 origin 0 0 0 id @F2

;
;join on range z -10,-7
;join on range z 10,-3
gen edge 0.5
;
prop mat=1 dens 2000 bulk 20e9 g 10e9
change mat 1 cons 1

prop jmat=1 jkn 5e11 jks 2.5e11 jfric 32 jcoh 0 jtens 0.0

prop jmat=2 jkn 5e11 jks 2.5e11 jfric 32 jcoh 1e6 jtens 0.0

change jmat 1 cons 1
change jmat 2 range mint 1 1 ori dip 45 ori dd 315

insitu stress -50e6,-55e6,-83e6 0,0,0 nodisp
insitu pp 27e6 nodisp


bound stress -50e6 0 0 0 0 0 range x -10.0
bound stress -50e6 0 0 0 0 0 range x 10.0
bound stress 0 -55e6 0 0 0 0 range y -10.0
bound stress 0 -55e6 0 0 0 0 range y 10.0
bound stress 0 0 -83e6 0 0 0 range z 0.0
bound zvel 0.0 range z -10.0


hist unbal

;S3 horizontal

his s3 -10 1.5 -5.0
his s3 -9 1.5 -5.0
his s3 -8 1.5 -5.0
```

```
his s3 -7.0 1.5 -5.0
his s3 -6.0 1.5 -5.0
his s3 -5.0 1.5 -5.0
his s3 -4 1.5 -5.0
his s3 -3 1.5 -5.0
his s3 -2 1.5 -5.0
his s3 -1 1.5 -5.0
his s3 -0.5 1.5 -5.0
his s3 -0.25 1.5 -5.0
his s3 0.0 1.5 -5.0
his s3 0.25 1.5 -5.0
his s3 0.5 1.5 -5.0
his s3 1 1.5 -5.0
his s3 2 1.5 -5.0
his s3 3 1.5 -5.0
his s3 4 1.5 -5.0
his s3 5 1.5 -5.0
his s3 6 1.5 -5.0
his s3 7 1.5 -5.0
his s3 8 1.5 -5.0
his s3 9 1.5 -5.0
his s3 10 1.5 -5.0

;S1horizontal
his s1 -10 1.5 -5.0
his s1 -9 1.5 -5.0
his s1 -8 1.5 -5.0
his s1 -7.0 1.5 -5.0
his s1 -6.0 1.5 -5.0
his s1 -5.0 1.5 -5.0
his s1 -4 1.5 -5.0
his s1 -3 1.5 -5.0
his s1 -2 1.5 -5.0
his s1 -1 1.5 -5.0
his s1 -0.5 1.5 -5.0
his s1 -0.25 1.5 -5.0
his s1 0.0 1.5 -5.0
his s1 0.25 1.5 -5.0
his s1 0.5 1.5 -5.0
his s1 1 1.5 -5.0
his s1 2 1.5 -5.0
his s1 3 1.5 -5.0
his s1 4 1.5 -5.0
his s1 5 1.5 -5.0
his s1 6 1.5 -5.0
his s1 7 1.5 -5.0
his s1 8 1.5 -5.0
his s1 9 1.5 -5.0
his s1 10 1.5 -5.0

;Sdis
his sdis -10 1.5 -5.0
his sdis -9 1.5 -5.0
his sdis -8 1.5 -5.0
his sdis -7.0 1.5 -5.0
his sdis -6.0 1.5 -5.0
his sdis -5.0 1.5 -5.0
his sdis -4 1.5 -5.0
his sdis -3 1.5 -5.0
his sdis -2 1.5 -5.0
his sdis -1 1.5 -5.0
his sdis -0.5 1.5 -5.0
his sdis -0.25 1.5 -5.0
his sdis 0.0 1.5 -5.0
his sdis 0.25 1.5 -5.0
his sdis 0.5 1.5 -5.0
his sdis 1 1.5 -5.0
```

```
his sdis 2 1.5 -5.0
his sdis 3 1.5 -5.0
his sdis 4 1.5 -5.0
his sdis 5 1.5 -5.0
his sdis 6 1.5 -5.0
his sdis 7 1.5 -5.0
his sdis 8 1.5 -5.0
his sdis 9 1.5 -5.0
his sdis 10 1.5 -5.0


cyc 800

reset disp jdisp

save F32C1

------------------------------

F32 C5

;elastic
new
poly brick -10,10 -10,10 -10,0
;join on
;jset dip 55 dd 90 origin 0,0,-5
;jset dip 15 dd 90 origin 0,0,-7
;jset dip 15 dd 90 origin 0,0,-3

def fault_id
  F1 = 1
  F2 = 2
end
@fault_id
jset dip 80 dd 90 spac 4 num 8 origin 0 0 0 id @F1

jset dip 45 dd 315 spac 4 num 8 origin 0 0 0 id @F2

;
;join on range z -10,-7
;join on range z 10,-3
gen edge 0.5
;
prop mat=1 dens 2000 bulk 20e9 g 10e9
change mat 1 cons 1

prop jmat=1 jkn 5e11 jks 2.5e11 jfric 32 jcoh 0 jtens 0.0

prop jmat=2 jkn 5e11 jks 2.5e11 jfric 32 jcoh 5e6 jtens 0.0

change jmat 1 cons 1
change jmat 2 range mint 1 1 ori dip 45 ori dd 315

insitu stress -50e6,-55e6,-83e6 0,0,0 nodisp
insitu pp 27e6 nodisp


bound stress -50e6 0 0 0 0 0 range x -10.0
bound stress -50e6 0 0 0 0 0 range x 10.0
bound stress 0 -55e6 0 0 0 0 range y -10.0
bound stress 0 -55e6 0 0 0 0 range y 10.0
bound stress 0 0 -83e6 0 0 0 range z 0.0
bound zvel 0.0 range z -10.0


hist unbal
```

```
;S3 horizontal

his s3 -10 1.5 -5.0
his s3 -9 1.5 -5.0
his s3 -8 1.5 -5.0
his s3 -7.0 1.5 -5.0
his s3 -6.0 1.5 -5.0
his s3 -5.0 1.5 -5.0
his s3 -4 1.5 -5.0
his s3 -3 1.5 -5.0
his s3 -2 1.5 -5.0
his s3 -1 1.5 -5.0
his s3 -0.5 1.5 -5.0
his s3 -0.25 1.5 -5.0
his s3 0.0 1.5 -5.0
his s3 0.25 1.5 -5.0
his s3 0.5 1.5 -5.0
his s3 1 1.5 -5.0
his s3 2 1.5 -5.0
his s3 3 1.5 -5.0
his s3 4 1.5 -5.0
his s3 5 1.5 -5.0
his s3 6 1.5 -5.0
his s3 7 1.5 -5.0
his s3 8 1.5 -5.0
his s3 9 1.5 -5.0
his s3 10 1.5 -5.0

;S1horizontal
his s1 -10 1.5 -5.0
his s1 -9 1.5 -5.0
his s1 -8 1.5 -5.0
his s1 -7.0 1.5 -5.0
his s1 -6.0 1.5 -5.0
his s1 -5.0 1.5 -5.0
his s1 -4 1.5 -5.0
his s1 -3 1.5 -5.0
his s1 -2 1.5 -5.0
his s1 -1 1.5 -5.0
his s1 -0.5 1.5 -5.0
his s1 -0.25 1.5 -5.0
his s1 0.0 1.5 -5.0
his s1 0.25 1.5 -5.0
his s1 0.5 1.5 -5.0
his s1 1 1.5 -5.0
his s1 2 1.5 -5.0
his s1 3 1.5 -5.0
his s1 4 1.5 -5.0
his s1 5 1.5 -5.0
his s1 6 1.5 -5.0
his s1 7 1.5 -5.0
his s1 8 1.5 -5.0
his s1 9 1.5 -5.0
his s1 10 1.5 -5.0

;Sdis
his sdis -10 1.5 -5.0
his sdis -9 1.5 -5.0
his sdis -8 1.5 -5.0
his sdis -7.0 1.5 -5.0
his sdis -6.0 1.5 -5.0
his sdis -5.0 1.5 -5.0
his sdis -4 1.5 -5.0
his sdis -3 1.5 -5.0
his sdis -2 1.5 -5.0
his sdis -1 1.5 -5.0
his sdis -0.5 1.5 -5.0
```

```
his sdis -0.25 1.5 -5.0
his sdis 0.0 1.5 -5.0
his sdis 0.25 1.5 -5.0
his sdis 0.5 1.5 -5.0
his sdis 1 1.5 -5.0
his sdis 2 1.5 -5.0
his sdis 3 1.5 -5.0
his sdis 4 1.5 -5.0
his sdis 5 1.5 -5.0
his sdis 6 1.5 -5.0
his sdis 7 1.5 -5.0
his sdis 8 1.5 -5.0
his sdis 9 1.5 -5.0
his sdis 10 1.5 -5.0


cyc 800

reset disp jdisp

save F32C5
--------------------------

F32 C10

;elastic
new
poly brick -10,10 -10,10 -10,0
;join on
;jset dip 55 dd 90 origin 0,0,-5
;jset dip 15 dd 90 origin 0,0,-7
;jset dip 15 dd 90 origin 0,0,-3

def fault_id
  F1 = 1
  F2 = 2
end
@fault_id
jset dip 80 dd 90 spac 4 num 8 origin 0 0 0 id @F1

jset dip 45 dd 315 spac 4 num 8 origin 0 0 0 id @F2

;
;join on range z -10,-7
;join on range z 10,-3
gen edge 0.5
;
prop mat=1 dens 2000 bulk 20e9 g 10e9
change mat 1 cons 1

prop jmat=1 jkn 5e11 jks 2.5e11 jfric 32 jcoh 0 jtens 0.0

prop jmat=2 jkn 5e11 jks 2.5e11 jfric 32 jcoh 10e6 jtens 0.0

change jmat 1 cons 1
change jmat 2 range mint 1 1 ori dip 45 ori dd 315

insitu stress -50e6,-55e6,-83e6 0,0,0 nodisp
insitu pp 27e6 nodisp


bound stress -50e6 0 0 0 0 0 range x -10.0
bound stress -50e6 0 0 0 0 0 range x 10.0
bound stress 0 -55e6 0 0 0 0 range y -10.0
bound stress 0 -55e6 0 0 0 0 range y 10.0
bound stress 0 0 -83e6 0 0 0 range z 0.0
bound zvel 0.0 range z -10.0
```

```
hist unbal

;S3 horizontal

his s3 -10 1.5 -5.0
his s3 -9 1.5 -5.0
his s3 -8 1.5 -5.0
his s3 -7.0 1.5 -5.0
his s3 -6.0 1.5 -5.0
his s3 -5.0 1.5 -5.0
his s3 -4 1.5 -5.0
his s3 -3 1.5 -5.0
his s3 -2 1.5 -5.0
his s3 -1 1.5 -5.0
his s3 -0.5 1.5 -5.0
his s3 -0.25 1.5 -5.0
his s3 0.0 1.5 -5.0
his s3 0.25 1.5 -5.0
his s3 0.5 1.5 -5.0
his s3 1 1.5 -5.0
his s3 2 1.5 -5.0
his s3 3 1.5 -5.0
his s3 4 1.5 -5.0
his s3 5 1.5 -5.0
his s3 6 1.5 -5.0
his s3 7 1.5 -5.0
his s3 8 1.5 -5.0
his s3 9 1.5 -5.0
his s3 10 1.5 -5.0

;S1horizontal
his s1 -10 1.5 -5.0
his s1 -9 1.5 -5.0
his s1 -8 1.5 -5.0
his s1 -7.0 1.5 -5.0
his s1 -6.0 1.5 -5.0
his s1 -5.0 1.5 -5.0
his s1 -4 1.5 -5.0
his s1 -3 1.5 -5.0
his s1 -2 1.5 -5.0
his s1 -1 1.5 -5.0
his s1 -0.5 1.5 -5.0
his s1 -0.25 1.5 -5.0
his s1 0.0 1.5 -5.0
his s1 0.25 1.5 -5.0
his s1 0.5 1.5 -5.0
his s1 1 1.5 -5.0
his s1 2 1.5 -5.0
his s1 3 1.5 -5.0
his s1 4 1.5 -5.0
his s1 5 1.5 -5.0
his s1 6 1.5 -5.0
his s1 7 1.5 -5.0
his s1 8 1.5 -5.0
his s1 9 1.5 -5.0
his s1 10 1.5 -5.0

;Sdis
his sdis -10 1.5 -5.0
his sdis -9 1.5 -5.0
his sdis -8 1.5 -5.0
his sdis -7.0 1.5 -5.0
his sdis -6.0 1.5 -5.0
his sdis -5.0 1.5 -5.0
his sdis -4 1.5 -5.0
```

```
his sdis -3 1.5 -5.0
his sdis -2 1.5 -5.0
his sdis -1 1.5 -5.0
his sdis -0.5 1.5 -5.0
his sdis -0.25 1.5 -5.0
his sdis 0.0 1.5 -5.0
his sdis 0.25 1.5 -5.0
his sdis 0.5 1.5 -5.0
his sdis 1 1.5 -5.0
his sdis 2 1.5 -5.0
his sdis 3 1.5 -5.0
his sdis 4 1.5 -5.0
his sdis 5 1.5 -5.0
his sdis 6 1.5 -5.0
his sdis 7 1.5 -5.0
his sdis 8 1.5 -5.0
his sdis 9 1.5 -5.0
his sdis 10 1.5 -5.0


cyc 800

reset disp jdisp

save F32C10

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```