EFFECT OF BOREHOLE - INDUCED STRESSES ON FRACTURE PERMEABILITY

Chanodom Lertsuriyakul

A Thesis Submitted in Partial Fulfillment of the Requirements for the

Degree of Master of Engineering in Geotechnology

Suranaree University of Technology

Academic Year 2012

ผลกระทบของความเค้นที่เกิดจากหลุมเจาะต่อค่าความซึมผ่านของรอยแตก

นายชโนดม เลิศสุริยะกุล

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิศวกรรมศาสตรมหาบัณฑิต
สาขาวิชาเทคโนโลยีธรณี
มหาวิทยาลัยเทคโนโลยีสุรนารี
ปีการศึกษา 2555

EFFECT OF BOREHOLE - INDUCED STRESSES ON FRACTURE PERMEABILITY

Suranaree University of Technology has approved this thesis submitted in partial fulfillment of the requirements for a Master's Degree.

Thesis Examining Committee

____

(Assoc. Prof. Kriangkrai Trisarn)

Chairperson

____

(Dr. Prachya Tepnarong)

Member (Thesis Advisor)

____

(Assoc. Prof. Dr. Kittitep Fuenkajorn)

Member

____

(Prof. Dr. Sukit Limpijumnong)

Vice Rector for Academic Affairs

____

(Assoc. Prof. Flt. Lt. Dr. Kontorn Chamniprasart)

Dean of Institute of Engineering

ชโนดม เลิศสุริยะกุล : ผลกระทบของความเค้นที่เกิดจากหลุมเจาะต่อค่าความซึมผ่านของรอยแตก (EFFECT OF BOREHOLE – INDUCED STRESSES ON FRACTURE PERMEABILITY) อาจารย์ที่ปรึกษา : อาจารย์ ดร.ปรัชญา เทพณรงค์, 49 หน้า.

การทดสอบค่าความซึมผ่านในรอยแตกบริเวณรอบหลุมเจาะภายในห้องปฏิบัติการจึงได้ดำเนินการเพื่อหาผลกระทบของความเค้นกดบนรอยแตก ตัวอย่างหินทรายชุดภูกระดึงรูปทรงกระบอกถูกจัดเตรียมให้มีเส้นผ่าศูนย์กลาง 18.6 เซนติเมตร สูง 15 เซนติเมตร ตัวอย่างหินมีรูทะลุที่จุดศูนย์กลางเท่ากับ 3.3 เซนติเมตร ตัวอย่างหินมีความเป็นเนื้อเดียวกันและมีคุณสมบัติทึบน้ำ ตัวอย่างหินจะถูกทำรอยแตกผ่ากลางรูเจาะด้วยวิธีการให้แรงแบบเส้นซึ่งขนานไปตามแกนกลางของตัวอย่าง การทดสอบค่าความซึมผ่านในรอยแตกทำโดยใช้การอัดน้ำเข้าสู่ตัวอย่างหินภายใต้การให้แรงในแนวดิ่งแบบคงที่โดยผันแปรมุมที่รอยแตกกระทำกับแรงกดทีละ 15 องศา จนกระทั่งครบรอบวัฏจักรและทำการทดสอบอย่างต่อเนื่อง 3 วัฏจักร ค่าความซึมผ่านในรอยแตกคำนวณได้จากอัตราการไหลของน้ำที่วัดได้จากการทดสอบค่าความเค้นเฉลี่ยในแนวดิ่งบนระนาบตัวอย่างมีค่าผันแปรตั้งแต่ 0.63 เมกะปาสคาล ถึง 1.85 เมกะปาสคาล การจำลองด้วยแบบจำลองทางคอมพิวเตอร์ได้ถูกนำมาใช้เพื่อตรวจสอบการกระจายตัวของความเค้นบนรอยแตกภายใต้สภาวะที่ถูกความเค้นกระทำในทิศทางที่ต่างกัน ผลที่ได้สอดคล้องกับการคำนวณด้วยสมการสำเร็จรูปในสภาวะที่มีแรงกระทำจากภายนอก

ผลจากการการทดสอบสรุปว่าเมื่อค่าความเค้นในแนวตั้งฉากเพิ่มขึ้นค่าความซึมผ่านในรอยแตกจะมีค่าลดลง เมื่อรอยแตกมีทิศทางเบี่ยงเบนจากความเค้นที่กระทำลงบนตัวอย่างหินค่าความเค้นเฉือนจะส่งผลให้ค่าความซึมผ่านในรอยแตกเพิ่มขึ้น นอกจากนี้ผลที่ได้ยังแสดงให้เห็นถึงความไม่คืนตัวของช่องเปิดเผยของรอยแตกโดยสังเกตจากค่าความซึมผ่านในวัฏจักรที่ 2 และวัฏจักรที่ 3 ที่มีค่าความซึมผ่านต่ำกว่าวัฏจักรแรกโดยค่าความซึมผ่านในรอยแตกที่วัดได้มีค่าอยู่ระหว่าง 1×10^{-18} ตารางเมตร ถึง 1.5×10^{-15} ตารางเมตร

สาขาวิชา เทคโนโลยีธรณี ลายมือชื่อนักศึกษา __________

ปีการศึกษา 2555 ลายมือชื่ออาจารย์ที่ปรึกษา __________

CHANODOM LERTSURIYAKUL : EFFECT OF BOREHOLE – INDUCED STRESSES ON FRACTURE PERMEABILITY. THESIS ADVISOR : PRACHYA TEPNARONG, Ph.D., 49 PP.

FRACTURE/ PERMEABILITY/BOREHOLE/ STRESS

The objective of this research is to experimentally study the permeability of rock fracture around borehole**.** The effort primarily involves laboratory flow testing of rock fractures under various stress stage and the orientations of fracture. The rock specimens are prepared from Phu Kradung sandstone to obtain hollow cylinders having outside and inside diameters of 18.6 and 3.3 cm with a length of 15 cm. The rock is uniform and effectively impermeable. A radial fracture is artificially made by tension inducing method. It cuts through the borehole axis and along the specimen diameter. After applying a constant diametrical loading, the water is injected under constant head into the center hole. The fracture permeability is determined for various fracture orientations with respect to the vertical loading direction with 15° apart. The flow tests are repeated 3 times under each vertical load to assess the permanent closure of the fracture under loading. The diametrical loads are progressively increased from 0.63 MPa to 1.85 MPa. Finite difference analyses have been performed to calculate the normal and shear stress distributions on the fracture under various orientations.

The results indicate that the increases of the normal stresses rapidly decrease the fracture permeability. When the normal of fracture is deviated from the loading direction, the shear stress can increase the fracture permeability. A permanent closure of the fracture is observed as evidenced by the permanent reduction of the fracture permeability measured from the second and third cycles. The changes of aperture, water flow rate, and applied water pressures are used to calculate the changes of the fracture permeability. The fracture permeability is in the range between 1×10^{-18} m^2 and 1.5×10^{-15} m^2.

School of Geotechnology____ Student's Signature______________________

Academic Year 2012 Advisor's Signature______________________

ACKNOWLEDGEMENTS

The author wishes to acknowledge the support from the Suranaree University of Technology (SUT) who has provided funding for this research.

Grateful thanks and appreciation are given to Dr. Prachaya Tepnarong, thesis advisor, who lets the author work independently, but gave a critical review of this research. Many thanks are also extended to Assoc. Prof. Kriangkrai Trisarn and Assoc. Prof. Dr. Kittitep Fuenkajorn, who served on the thesis committee and commented on the manuscript.

Finally, I most gratefully acknowledge my parents and friends for all their supported throughout the period of this research.

Chanodom Lertsuriyakul

TABLE OF CONTENTS

Page

TABLE OF CONTENTS (Continued)

Page

LIST OF TABLES

Table **Page**

LIST OF FIGURES

Figure **Page**

LIST OF FIGURES (Continued)

Figure **Page**

SYMBOLS AND ABBREVIATIONS

a	=	Inner radial of opening
b	=	Width of the fracture
D	=	Diameter of the specimen
dp/dx	=	Pressure gradient along the length
e	=	Aperture of magnitude
e_h	=	Physical aperture
e_c	=	Equivalent cubic law aperture
JRC	=	Joint roughness coefficient
K	=	Hydraulic conductivity
K_n	=	Joint normal stiffness
K_s	=	Joint shear stiffness
k	=	Fracture permeability
k_c	=	Combined permeability
k_f	=	Individual fracture permeability
k_m	=	Intact rock permeability
P_1	=	Vertical stress
P_2	=	Lateral stress
q	=	Fluid flow rate
r	=	Variable radius
ε_v	=	Volumetric strain

SYMBOLS AND ABBREVIATIONS (Continued)

μ	=	Dynamic viscosity
θ	=	Fracture orientation
σ_r	=	Radial stress
σ_v	=	Vertical stress
σ_θ	=	Tangential stress
$\tau_{r\theta}$	=	Shear stress

CHAPTER I

INTRODUCTION

1.1 Background of problems and significance of the study

It has been difficult to predict the groundwater inundation and loss of drilling fluid in complex hydro-geological environments prevailing in boreholes and petroleum wells. This is primarily because of the lack of proper understanding of flow through porous media containing systems of fractures. Fluid flow through rock mass is normally complicated by the presence of fracture systems which represent the dominant flow path. Fracture apertures and hydraulic conductivity are the main factors governing the rock mass permeability. Xiao et al. (1999), Pyrak-Noltea and Morrisa (2000), Niemi et al. (1997), Indraratna and Ranjith (2001), Baghbanan and Jing (2008) and Akkrachattrarat et al. (2009) conclude from their experimental results that fracture permeability exponentially decreases with increasing normal stresses. The apertures and permeability of rock fractures are also affected by the shearing displacement (Auradou et al., 2006). The fracture flow measurements in the field also complicated by the local stress induced by the test hole. Knowledge and understanding of fluid flow near the openings surrounding by fractures are rare.

1.2 Research objectives

The objective of this research is to experimentally study the permeability of rock fracture around borehole**.** The effort primarily involves laboratory flow testing of rock fractures under various stress stages and orientations. The measurement results will be used to develop a constitutive equation relating the flow and stress gradient. The research findings can be of useful in determining the fracture permeability under in-situ stress conditions with varying fracture orientations.

1.3 Research methodology

As shown in Figure 1.1, the research methodology comprises 5 steps; literature review, sample collection and preparation, flow testing, development of mathematical relations and flow equations, and discussions and conclusions.

1.3.1 Literature review

Literature review is carried out to study the occurrence and classification of fractures, permeability of rock mass, apertures, and stress effects on fracture void geometry. The sources of information are from text books, journals, technical reports and conference papers. A summary of the literature review is given in the thesis.

1.3.2 Sample preparation

Sandstone samples are collected from the site. Phu Kradung sandstone is selected for this study. Sample preparation is carried out in the laboratory at the Suranaree University of Technology. Samples for the falling head test are prepared to have fractures area of about 18.5×15 centimeters. The fractures are artificially made in the laboratory by tension inducing method.

1.3.3 Flow test under various vertical stresses and fracture orientations

Constant head tests are conducted by injecting water into the center hole of cylindrical shape of sandstone. A constant diameter water pump is used to inject water pressure to one end of the specimen. The specimen is placed in load frame which is used to applied constant pressures to the rock and fracture. The applied pressures vary from 0.63 to 1.85 MPa. The injected water pressure is about 41.4 kPa which is controlled by using a regulating valve at the top of nitrogen gas tank. The acrylic tube is used to collect inflow rate of water. A single fracture is induced parallel to the specimen axis. The fracture permeability is determined for various orientations with 15° apart with respect to the loading direction. The measured flow rates at each pressure are measured to calculate the fracture permeability. The sample is rotation to induce different stress distribution on the fracture.

1.3.4 Numerical modeling

Finite difference mesh is constructed to graphically represent the rock specimen and loading platens. The computations use the linear finite element code "FLAC". The algorithm of this computer code is designed to calculate the normal and stress distribution. It is used to understand how the normal, shear and radial stresses change with respect to the fracture orientation.

Results from laboratory measurements in terms of rock permeability and stress states will be used to construct computer models to simulate or predict the fracture permeability under various fracture orientation.

1.3.5 Conclusion and thesis writing

All research activities, methods, and results are documented and complied in the thesis.

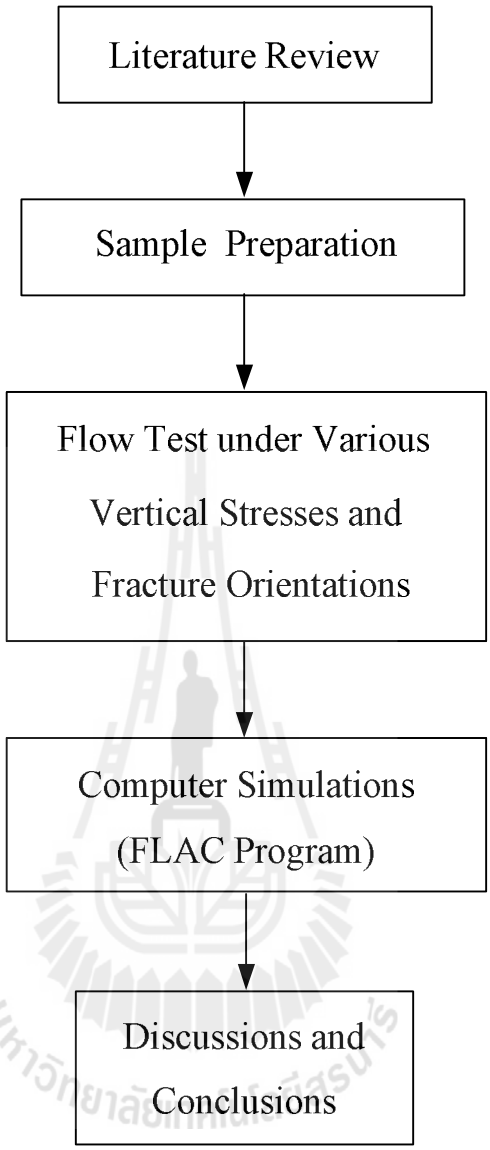

Figure 1.1 Research methodology

1.4 Scope and limitations of the study

The scope and limitations of the research include as follows.

1. Laboratory experiments are conducted on specimens from Phu Kradung sandstone

2. Testing on fractures is made under pressures ranging from 250 to 750 psi. Fracture permeability is determined by constant head flow testing.

3. Testing on fractures is made under without effect of joint roughness coefficient.

4. All tested fractures are artificially made in the laboratory.

5. All tests are conducted under ambient temperature.

6. The test fractures area is 18.5×15 square centimeters.

7. Water is used as flow medium.

8. No field testing is conducted.

1.5 Thesis contents

Chapter I introduces the thesis by briefly describing the background of problems and significance of the study. The research objectives, methodology, scope and limitations are identified. **Chapter II** summarizes the results of the literature review. **Chapter III** describes the sample preparation and laboratory experiment. **Chapter IV** presents the results obtained from the laboratory testing. **Chapter V** describes the numerical modeling to determine the stress distribution in rock around openings. **Chapter VI** concludes the research results, and provides recommendations for future research studies. **Appendix A** provides detailed of technical publication.

CHAPTER II

LITERATURE REVIEW

2.1 Introduction

This chapter summarizes the results of literature review carried out to improve an understanding of the effect of normal and shear stresses on the permeability around borehole. The topics reviewed here include the fluid flow in fracture rock, permeability of fracture rock, stiffness of fracture, and stress around borehole.

2.2 Literature review

Kirsch equations describe the elastic stresses around the hole in an infinite plate. The stress distributions around a borehole (σ_r, σ_θ, $\tau_{r\theta}$) can be calculated by Kirsch solution (Hoek and Brown, 1990).

$$\sigma_r = [(P_1 + P_2) / 2)][1 - (a^2/r^2)] + [(P_1 - P_2) / 2)][(1 - (4a^2/r^2)) +(3a^4/r^4)] \cos 2\theta \qquad (2.1)$$

$$\sigma_\theta = [(P_1 + P_2) / 2)][1 + (a^2/r^2)] - [(P_1 - P_2) / 2)][1 + (3a^4/r^4)] \cos 2\theta \qquad (2.2)$$

$$\tau_{r\theta} = - [(P_1 + P_2) / 2)][(1 + (2a^2/r^2) - (3a^4/r^4)] \cos 2\theta \qquad (2.3)$$

where σ_r is the stress in the direction of changing r, σ_θ is tangential stress, $\tau_{r\theta}$ is shear stress, P_1 is vertical stress, P_2 is lateral stress, a is inside radius of opening, r is variable radius and θ is the angle between vertical axis and radius.

Pyrak-Noltea and Morrisa (2000) stated that fracture specific stiffness and fluid flow through a single fracture under normal stress wear implicitly related through the geometry of the void space and contact area that comprise the fracture. Data from thirteen difference rock samples, each containing a single fracture, show that relationships between fracture specific stiffness and fluid flow through a fracture fall into two general classes of behavior. Fractures either fall on a loosely-defined universal curve relating fluid flow to fracture specific stiffness, or else the flow is weakly dependent on fracture specific stiffness. The second relationship shows that flow decreases slowly with increasing fracture specific stiffness. The first relationship shows that flow decreases rapidly for increases in fracture specific stiffness. To understand this behavior, computer simulations on simulated single fractures were performed to calculate fluid flow, fracture displacement, and fracture specific stiffness as a function of normal stress. Simulated fractures with spatially correlated and uncorrelated aperture distributions were studied. Fractures with spatially uncorrelated aperture distributions tend to exhibit a weak dependence of fluid flow on fracture specific stiffness because these fractures tend to have multiple connected paths across the sample which can support flow with uniformly distributed contact area. Thus an increment in stress will increase the stiffness of the fracture without greatly reducing the amount of fluid flow. On the other hand, fractures with spatially correlated aperture distributions tend to belong to the universal relationship because correlated fractures tend to have only one or two dominant flow paths and the contact area is limited to a few regions resulting in a compliant fracture. Thus an increment in stress on a spatially correlated fracture will result in an increase in stiffness and rapid decrease in fluid flow. These spatial correlations in fracture void geometry can be differentiated in the laboratory based on the observed fracture specific stiffness-fluid flow relationship for a single fracture under normal loading.

Indraratna and Ranjith (2001) state that permeability is simply the ability to conduct fluids, such as water, gas or multi-phase flows (e.g. water + gas, water + gas + oil) through porous media, such as soil or rocks. The permeability of discontinuities is referred to as the fracture permeability or the intrinsic permeability, whereas intact permeability is referred to as the matrix permeability. Therefore, the combined permeability of rock mass is given by

$$k_c = k_f + k_m \tag{2.4}$$

where k_c is the combined permeability of rock mass, and k_f and k_m are the individual fracture permeability and matrix permeability, respectively.

Under steady-state flow rate approach, for a cylindrical rock specimen, the coefficient of matrix/intact rock permeability (k_m) can be written using Darcy's law:

$$k_m = \frac{4q\mu}{\pi D^2 (dp/dx)} \tag{2.5}$$

where q is fluid flow rate through the specimen, dp/dx is the pressure gradient along the length (dx) of the specimen (Figure 2.1), μ is the dynamic viscosity of the fluid and D is the diameter of the specimen.

The equivalent aperture has to be referred to as the cubic law equivalent aperture. It is based on hydraulic tests. Frequently, and for simplicity, the equivalent cubic law aperture is referred to as the hydraulic aperture or mean aperture. For laminar fluid flow through parallel joint walls, the equivalent cubic law aperture (e_c) is defined by

$$e_c = \left[\frac{12q\mu}{(dp/dx)} \right]^{1/3} \tag{2.6}$$

where q = steady-state flow rate, b = width of the fracture, dp/dx = pressure gradient between two ends of the specimen and μ = dynamic viscosity of fluid.

For a smooth, planar joint having an aperture of magnitude (e), the fracture permeability for laminar flow is given by

$$k = \frac{e^2}{12} \tag{2.7}$$

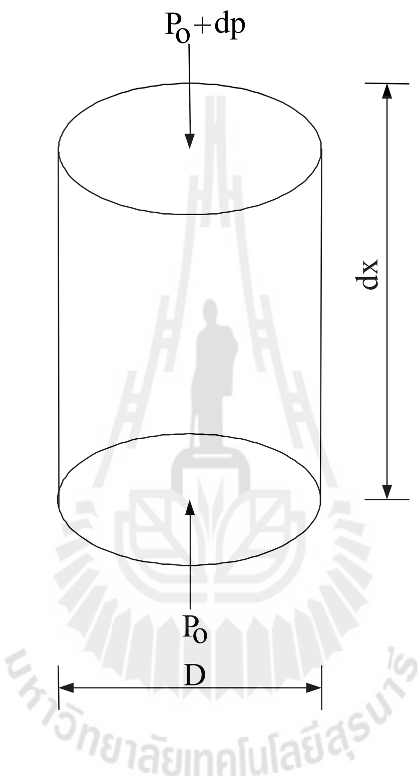

Figure 2.1 Pressure gradients along a rock specimen (Indraratna and Ranjith, 2001).

Auradou et al. (2006) investigate the effect on the transport properties of a fracture of a shear displacement *u* between its complementary surfaces experimentally and numerically. The shear displacement *u* induces an anisotropy of the fracture aperture field with a correlation length scaling of $|u|$, which is significantly larger in the direction perpendicular to *u*. This reflects the presence of long fluid flow channels perpendicular to the shear displacement, resulting in a higher effective permeability in that direction. Such channels will have a strong influence on the transport characteristics of a fracture, such as, for instance, its thermal exchange area, crucial for geothermal applications. Miscible displacement fronts in shear-displaced fractures obtained experimentally display a self-affine geometry with a characteristic exponent directly related to that of the fracture surfaces. They present a simple model, based on the channeling of the aperture field, which reproduces the front geometry when the mean flow is parallel to the channels created by the shear displacement

Baghbanan and Jing (2006) measure the permeability of fractured rocks considering the correlation between distributed fracture aperture and trace length, based on a newly developed correlation equation. The influence of the second moment of the lognormal distribution of apertures on the existence of representative elementary volume (REV), and the possibility of equivalent permeability tensor of the fractured rock mass, is examined by simulating flow through a large number of stochastic discrete fracture network (DFN) models of varying sizes and varying fracture properties. The REV size of the DFN models increases with the increase of the second moment of the lognormal distribution, for both the correlated and uncorrelated cases. The variation of overall permeability between different stochastic realizations is an order of magnitude larger when the aperture and length are correlated than when they are uncorrelated. The mean square error of the directional permeability increases with increasing value of the second moment of the lognormal distribution function, and good fitting to an ellipsis of permeability tensor can only be reached with very large sizes of DFN models, compared with the case of constant fracture aperture, regardless of fracture trace length.

Baghbanan and Jing (2008) studied the effect of stress on permeability and fluid flow patterns in fractured rock masses when distributed fracture aperture was correlated with fracture trace length, using a discrete element method (DEM). The basic assumptions are that the rock matrix is impermeable and linearly elastic, and that the fluid flows only in fractures. The results show that when small stress ratios (K = horizontal/vertical stress) are applied at the model boundaries, the overall permeability of the fracture network is generally decreased. However, contribution from a few large fractures of higher hydraulic conductivity prevents drastic reduction of the overall permeability, compared with models that assume uniform fracture apertures. With large values of the stress ratio, both the overall permeability and flow patterns are controlled by a combination of highly conductive larger fractures and fractures with shear slipping and dilation, with much increased overall permeability and shear-induced flow channeling. These results show significant difference between correlated and non-correlated aperture and fracture length distributions, and highlight more significant scale andstress dependence of hydro-mechanical behavior of fractures rocks when geometric parameters of rock fractures are correlated.

Akkrachattararat and Fuenkajorn (2009) determine the effects of anisotropic stress states on the permeability of porous rocks. Numerical modeling is performed to study the hydraulic conductivity of rock around single opening in infinite plate and of pillars between parallel circular openings under deviatoric stresses. The effort primarily involves conducting constant-head flow test on intact cylindrical sandstone specimens under a variety of confining pressures and deviatoric stresses. The results under deviatoric stress states suggest that before dilation strength the permeability decreases with increasing volumetric strain. This is probably due to the contraction of the pore spaces in the specimen. Within this stage the change of rock hydraulic conductivity to the change of volumetric strain ($\Delta K/\Delta \varepsilon_V$ ratio) decreases as increasing the confining pressures. After dilation strength the rock permeability increases with specimen dilation probably because of the initiation and propagation of micro-cracks due to the applied axial stress approaching failure. The results suggest that the hydraulic conductivity of rock around single circular tunnel increases from 107×10^{-9} to 120×10^{-9} m/s for PW sandstone, and 140×10^{-12} to 300×10^{-12} m/s for PK sandstone as the horizontal-vertical stress ratio decreases from 0.8 to 0.2. The hydraulic conductivity of rock pillars between parallel circular openings increases from 120×10^{-9} to 180×10^{-9} m/s for PW sandstone, and 350×10^{-12} to 1350×10^{-12} m/s for PK sandstone as the vertical stress increases from 10 to 40 MPa.

Suanprom et al. (2009) perform flow tests to determine hydraulic conductivity of tension-induced fractures under normal and shear stresses. The results indicate that the physical aperture e_p and hydraulic aperture e_h increase with shearing displacement, particularly under high normal stresses. The magnitudes of fracture permeability under no shear and under peak shear stress are similar. For both peak and residual regions, the physical apertures are about 5 to 10 times greater than the hydraulic apertures, as a result the fracture hydraulic conductivity determined from the physical aperture are about one to two orders of magnitudes greater than these determined from the equivalent hydraulic apertures. This is probably because the measured physical apertures do not consider the effect of fracture roughness that causes a longer flow path. The difference between the permeability under residual shear stress and that under peak stress becomes larger under higher normal stresses. The fracture hydraulic conductivities exponentially decrease with increasing the normal stresses. Their permeability is in the range between 0.1×10^{-3} m/s and 10×10^{-3} m/s.

CHAPTER III

SAMPLE PREPARATION

3.1 Introduction

Phu Kradung sandstone has been selected for use as rock sample here primarily because it has highly uniform texture, density and effectively impermeable. It is classified as fine-grained quartz sandstone with 48.8% quartz (0.1-1.5 mm), 46.10% albite (0.1-0.8 mm), 5.1% kaolinite (0.1-0.3 mm), 3% rock fragments (0.5-2mm), and 2% others (0.5-1 mm). The average density is 2.63 g/cc. Figure 3.1 shows some rock specimens after the fracture has been induced.

3.2 Sample preparation

Sample preparation is carried out in the laboratory at the Suranaree University of Technology. The cylindrical shaped specimen is 18.5 cm in diameter and 15 cm in length. A 3.3 cm diameter center hole is drilled along the specimen axis as shown in Figure 3.2. The fractures are artificially made by tension inducing method. The fracture area is 18.5 × 15 cm. The joint roughness coefficient (JRC) of the test fractures is about 6-8. Figure 3.3 shows tension-induced fracture along the diameter. Sealing the end of both specimen with gasket and set up connector tube for fracture flow testing, as shown in Figure 3.4

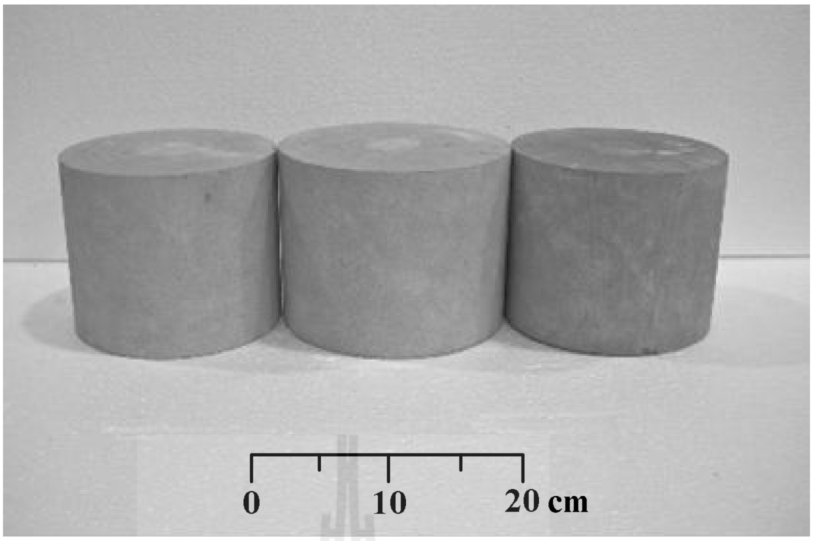

Figure 3.1 Some sandstone specimens prepared for constant head flow test with diameter of 18.5 cm and 15 cm in length.

Figure 3.2 Some rock specimen drilled along the specimen axis by drilling machine (model SBEL 1150) with diameter of 3.3 cm.

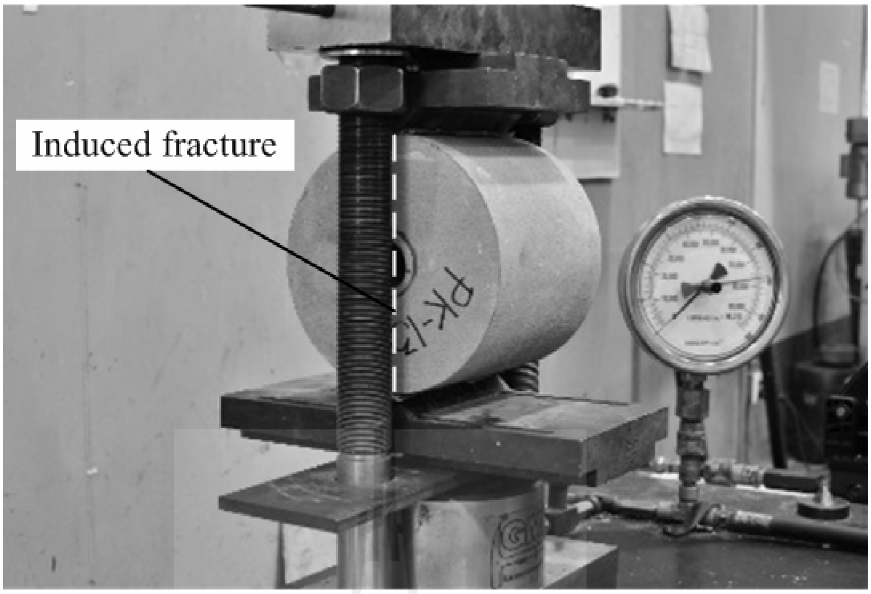

Figure 3.3 A cylindrical rock specimen is line-load to induce tensile fracture though borehole axis and along the specimen diameter.

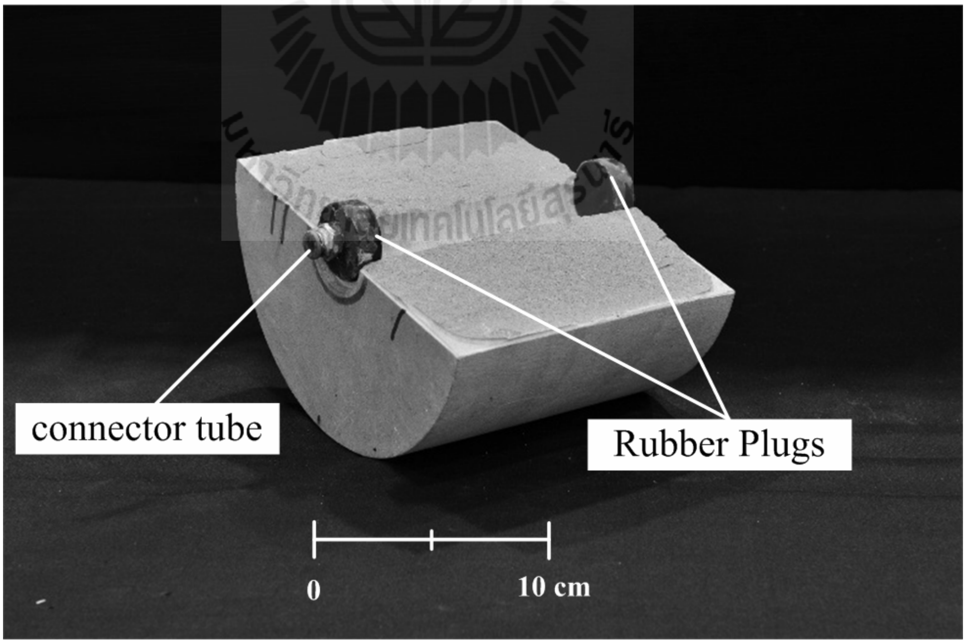

Figure 3.4 Rubber plug and connector tube are placed at both end of test hole.

CHAPTER IV

LABORATORY EXPERIMENT

4.1 Introduction

The objectiveof laboratory experiment is to determine the effects of the normal and shear stresses on the permeability of radial fracture. The results will be compared with the stress distribution calculated from computer simulation and close from solution. The effort primarily involves conducting constant-head flow tests on radial fracture under a variety of vertical stresses and fracture orientations. The permeability results are presented as a function of fracture orientation, stresses and fracture permeability.

4.2 Test method

Constant head flow test is conducted by injecting water into the center hole. The laboratory arrangement while the fracture is under vertical stress is shown in Figures 4.1 and 4.2. The injected water pressure is 41.4 kPa (6 psi) applied by a water pump to one end of the center hole. The other end is plugged. The water pressure is maintained constant by using a regulating valve at the top of a nitrogen gas tank of which connected to an acrylic tube to measure the inflow rate of water. Phu Kradung sandstone with radial fracture is placed in a pair of semi-cylindrical load frames to apply vertical stress perpendicular to the specimen axis. Neoprene sheets are placed between the loading platens and the rock surfaces to minimize the friction. This load configuration imposes an anisotropic stress to the rock and fracture around test hole. The fracture permeability is determined for various orientations with 15° apart with respect to the loading direction, as shown in Figure 4.3. The fracture rotations are made up to 3 cycles to assess the permanent deformation of the aperture. The vertical stresses are then progressively increased from 0.63, 1.24 to 1.85 MPa (250, 500 and 750 psi). The measured flow rates under each vertical load are used to calculate the fracture aperture and permeability. The test is conducted for 6 hours for each stress condition. Up to 4 samples have been tested.

Assuming that the Darcy's law is valid, the equivalent cubic law is applied to determine the aperture (e_c) from the flow test results, as follows (Indraratna and Ranjith, 2001):

$$e_c = [[12q\mu] / [b(dp/dx)]]^{1/3} \quad (4.1)$$

where q is steady-state water flow rate (cm^2/s), μ is the dynamic viscosity of the water ($N{\cdot}s/cm^2$), b = width of the fracture (cm), dp/dx is the pressure gradient along the length of the specimen.

The fracture permeability (k) can then be calculated by (Indraratna and Ranjith, 2001):

$$k = e^2/12 \quad (4.2)$$

where e is parallel plate aperture. The vertical stress (σ_v) is calculated by dividing the vertical load by the fracture area. The calculation assumed that the Phu Kradung sandstone is effectively impermeable (Akkrachattrarat et al., 2009)

4.3 Test results

Figures 4.4 through 4.7 give the results of fracture permeability as a function of fracture orientation for samples No.1 through 4. The fracture permeability varies as it rotates with respect to the loading direction. A permanent closure of the fracture under loading is observed as evidenced by the permanent reduction of the fracture permeability measured from the second and third cycles of testing. The fracture permeability decreases as the applied stresses increase. Increasing the vertical stresses from 0.63 MPa to 1.85 MPa can reduce the permeability by up to one order of magnitude. It is believed that the permeability variation with the fracture rotation is primarily due to the combined effects of the normal (tangential) and shear stresses induced on the fracture plane, providing that the radial stress has no effect on the fracture closure.

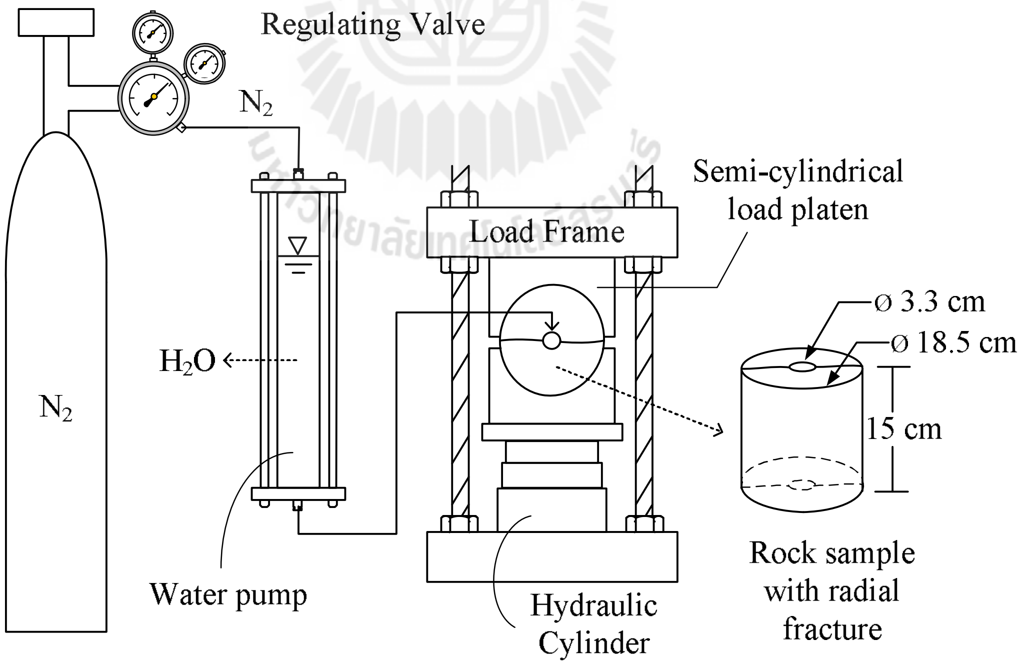

Figure 4.1 Laboratory arrangement for constant head flow tests of radial fracture under vertical stresses.

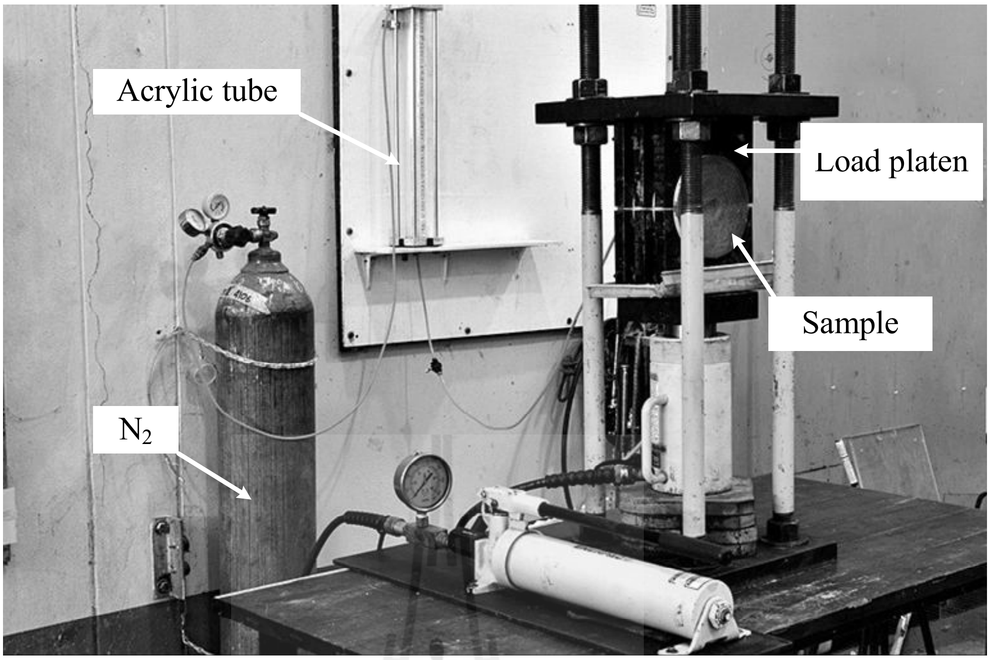

Figure 4.2 Arrangement for constant head flow tests of radial fracture under various vertical stresses and fracture orientations.

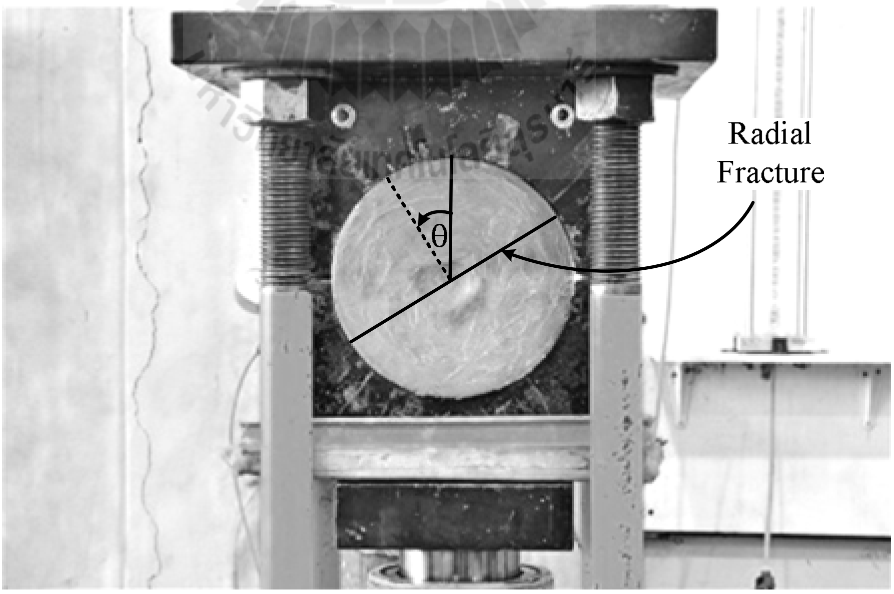

Figure 4.3 Rock sample with radial fracture.

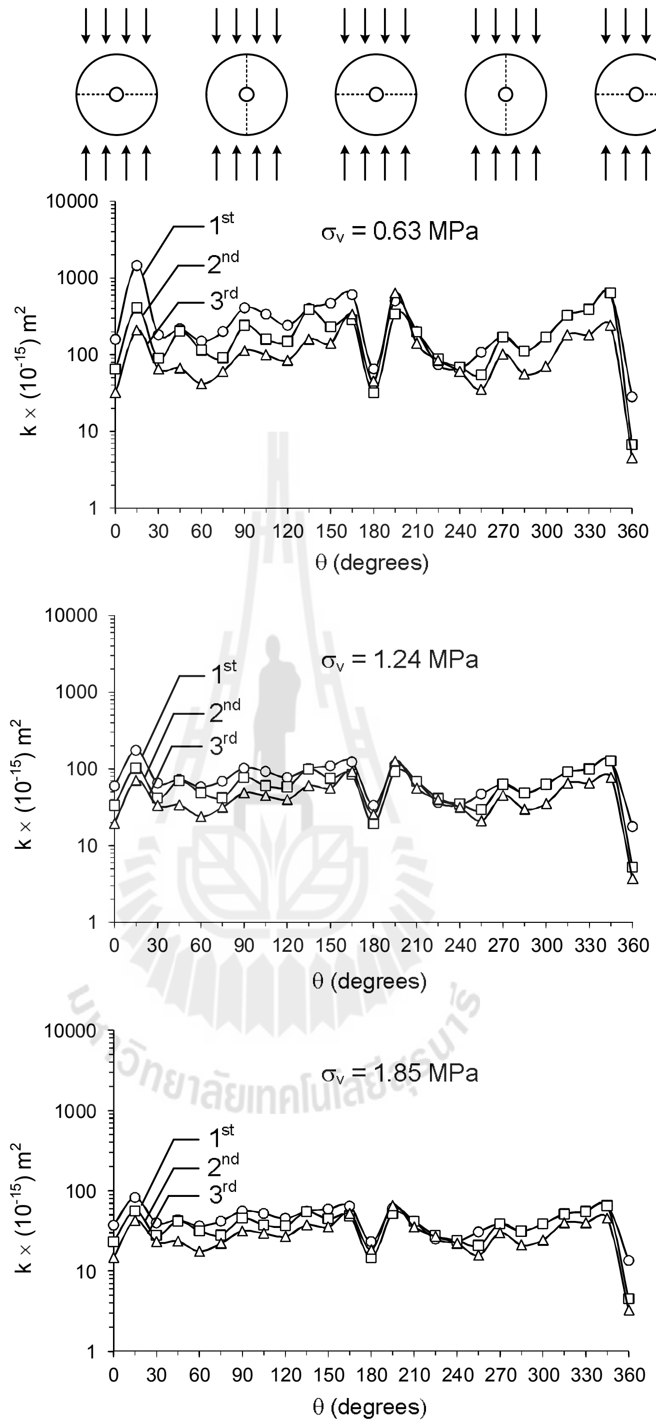

Figure 4.4 Fracture permeability as a function of fracture orientation for sample PKSS-01.

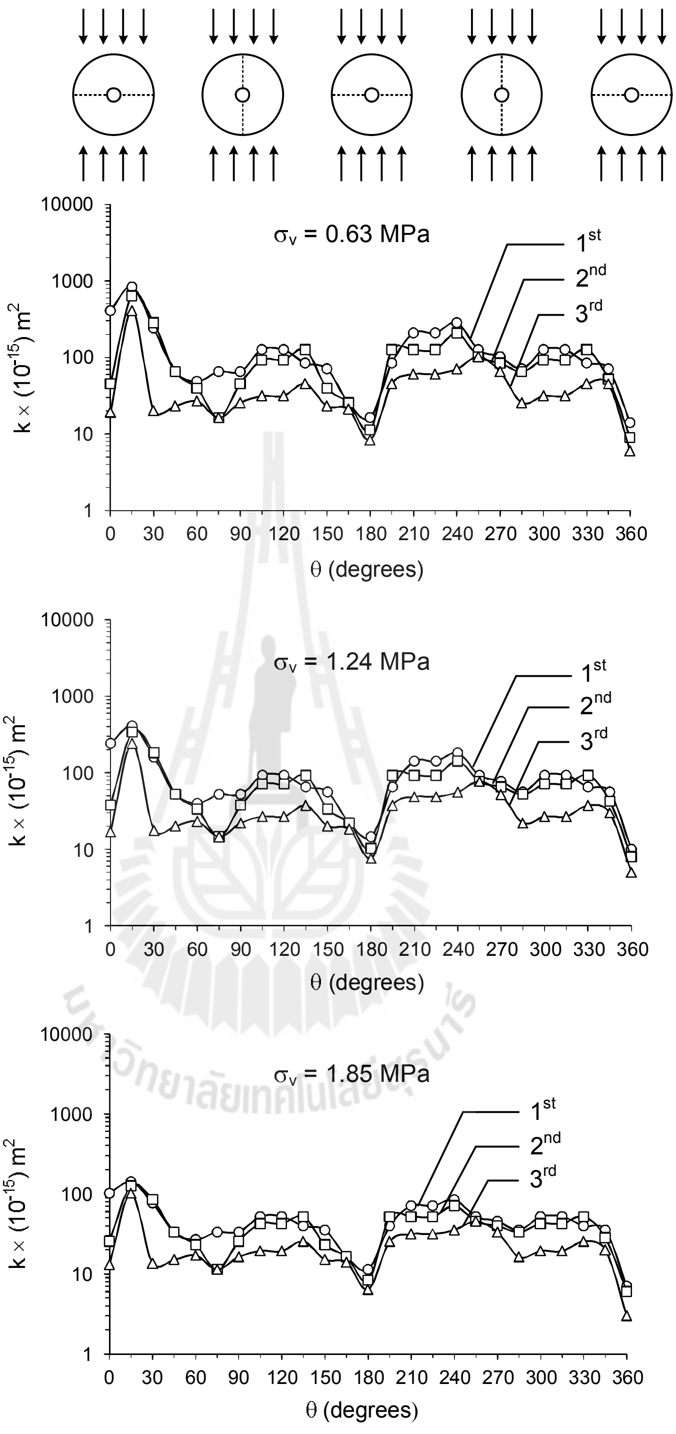

Figure 4.5 Fracture permeability as a function of fracture orientation for sample PKSS-02.

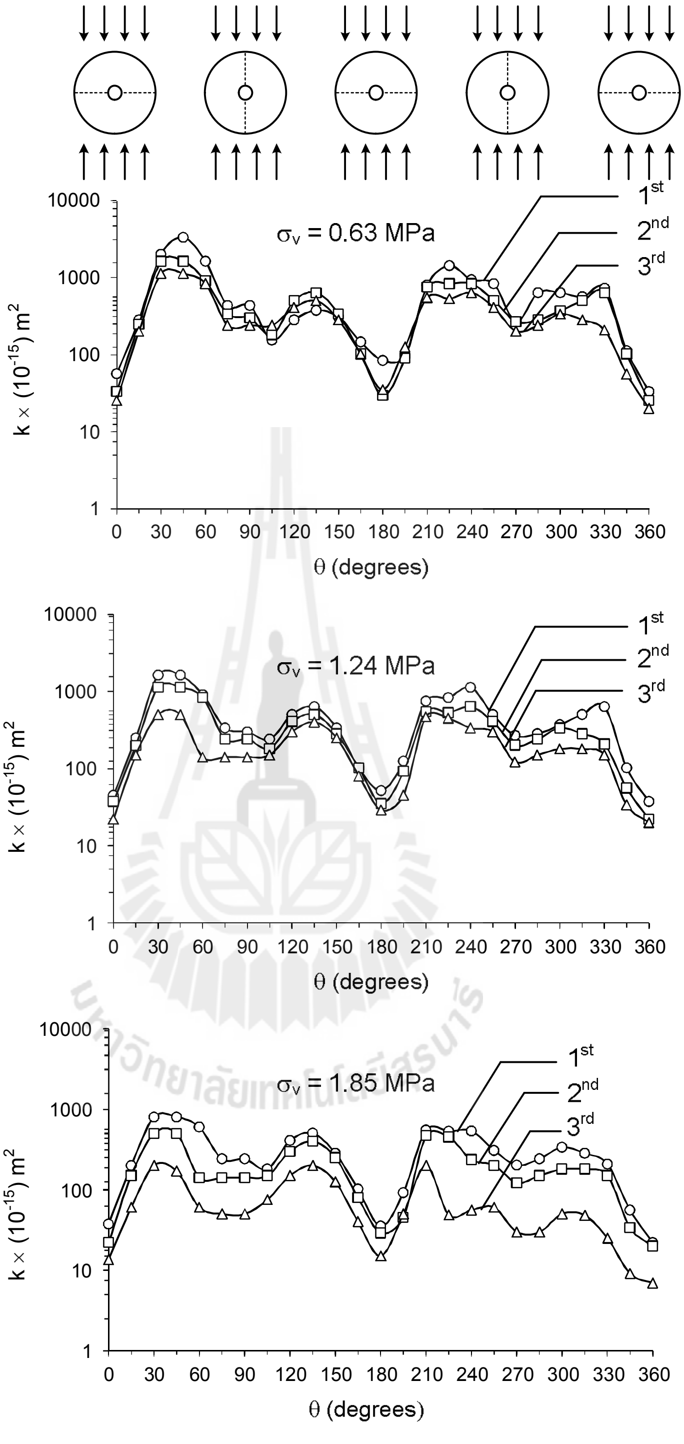

Figure 4.6 Fracture permeability as a function of fracture orientation for sample PKSS-03.

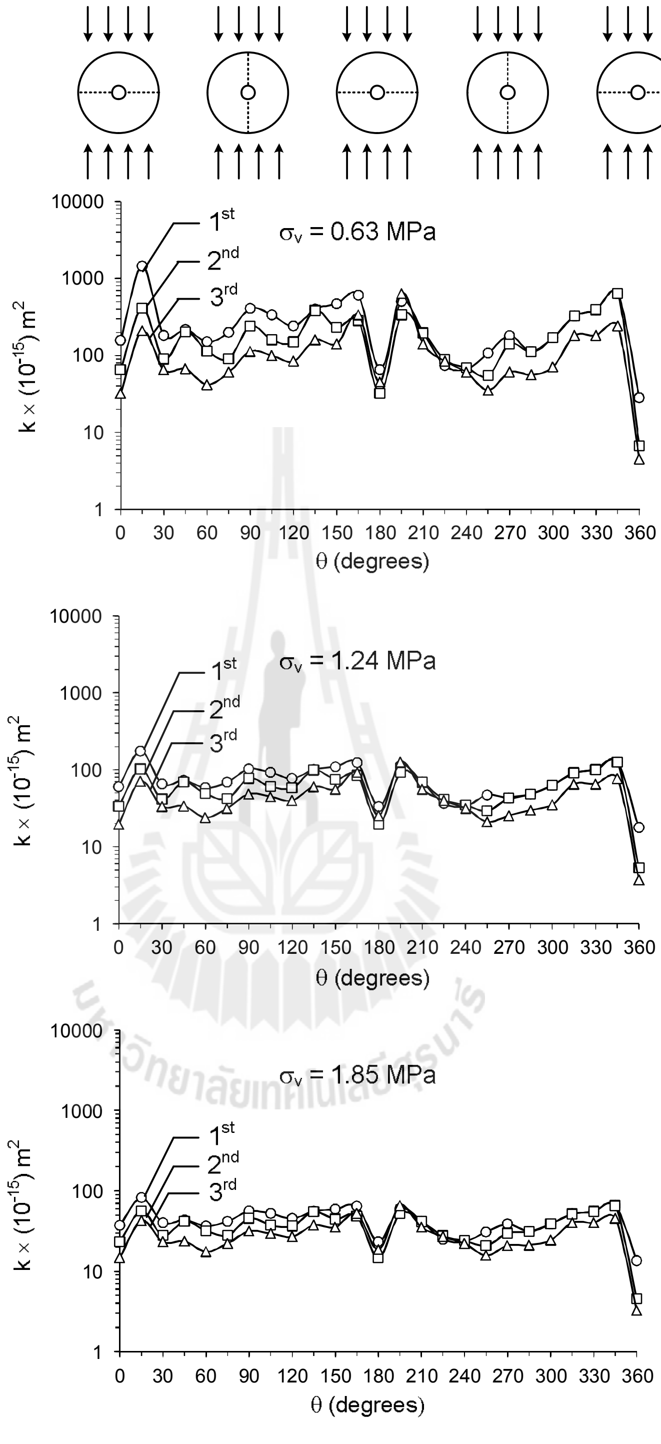

Figure 4.7 Fracture permeability as a function of fracture orientation for sample PKSS-04.

4.4 Discussions

The results indicate that the increases of the normal stresses rapidly decrease the fracture permeability. When the normal of fracture is deviated from loading direction, the normal stress on the fracture is reduced and the shear stress increases the fracture permeability. The flow test results from different test cycles show parallel patterns of the permeability which indicate that the test procedure and results are repeatable and that the permeability variations are due to the nature of the fracture flow under rock stresses not due to the method of measurements. It can be postulated that the permeability of radial fractures intersecting the borehole is in part governed by the normal and shear stresses on the fracture plane. The permeability tends to be low when the fracture plane is normal to the loading direction (θ = 0 and 180°, maximum normal stress), and high when it is parallel to the loading direction (θ = 90° and 270°, minimum normal stress). If only normal stresses are considered the fracture permeability should decreases from its maximum values at θ = 0 and 180° to its minimum values at θ = 90° and 270°. Under these orientations the shear stresses are zero and have no effect on the permeability. The results imply that the shear stress can increase the fracture permeability. The fracture permeability under anisotropic stresses depends on both normal and shear stresses. The effects from each stress are probably affected by the fracture roughness and asperities.

CHAPTER V

NUNERICAL MODELING

5.1 Objective

The numerical modeling performed in this study aims at studying how the normal, shear and radial stress change with respect to the fracture orientation. The finite difference analyses are performed using FLAC (Itasca, 1992). The results are used to compare with the close form solution and to help explain the results of fracture flow test. Properties of Phu Kradung sandstone are used in the numerical modeling.

5.2 Finite difference analyses

Finite difference analyses have been performed to calculate the normal and shear stress distributions on the fracture under various orientations. Figure 5.1 shows the two-dimensional finite difference mesh representing the cross-section of the loading platens and rock specimen. The fracture in the model can be defined for different orientations with respect to the loading direction. The bulk modulus and shear modulus of the sandstone are determined by Walsri et al. (2009) as 0.38 GPa and 19.3 GPa. The joint normal and shear stiffness values (K_n and K_s) for the fracture in the Phu Kradung sandstone are determined by Akkrachattraratet et al. (2009) as 4.8 GPa/m and 11 GPa/m. The joint friction angle and cohesion used in the simulations are 50° and 19 MPa. They are obtained from the direct shear testing conducted by Akkrachattrarat et al. (2009). All simulations assume plane strain condition. Table 1 summarizes the mechanical properties used in the calculation.

Table 5.1 Summary of the basic properties used in the FLAC simulation. (Mechanics of Material by Gere and Timoshenko, 1997).

Mechanical properties	**PK sandstone**	**Steel**
Elastic Modulus (GPa)	7.7	200
Poisson's Ratio	0.38	0.3
Cohesion (MPa)	19	-
Tension (MPa)	8.7	-
Internal Friction Angle (degrees)	50	-
Dilation Angle (degrees)	25	-

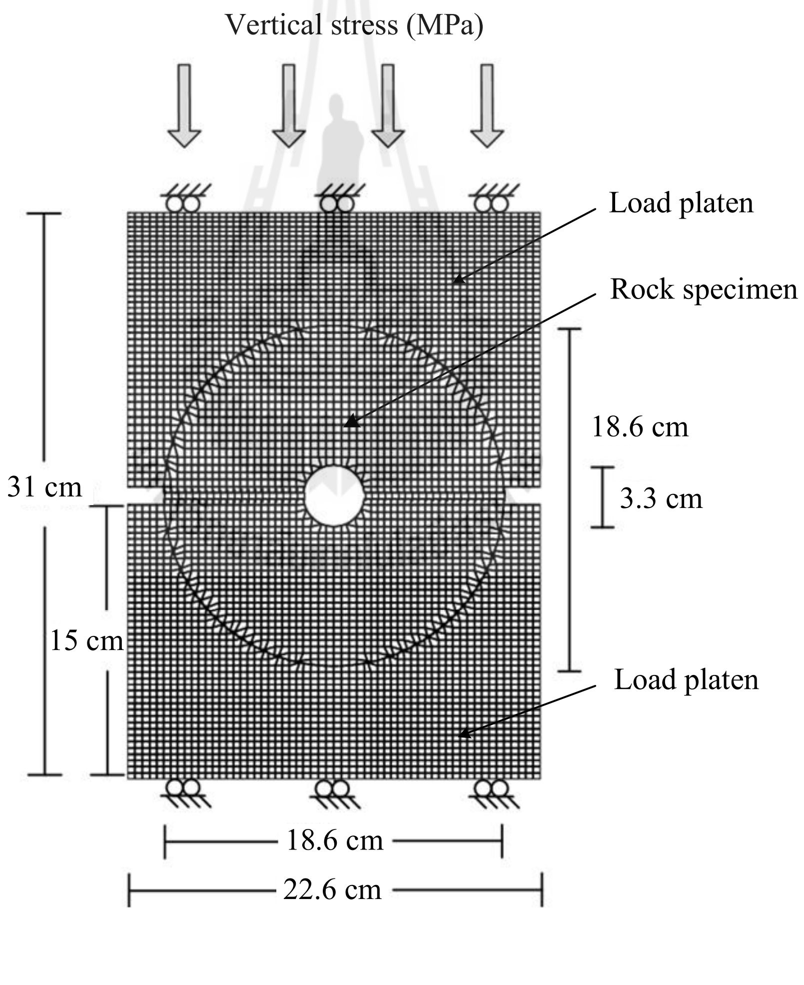

Figure 5.1 Finite difference mesh constructed to represent the test specimen and loading platens.

5.3 Close form solution

The stress distributions around borehole (σ_r, σ_θ, $\tau_{r\theta}$) are also calculated by Kirsch's solution (Hoek and Brown, 1990) to compare the results with those of the simulation. Both methods show similar distributions for the normal (tangential), shear and radial stresses on the fracture plane. Figures 5.2 through 5.4 compare the stresses obtained from the two methods for θ = 0, 45° and 90°. The stress results are normalized by the applied stress σ_v in the figures. The close agreements of the results obtained from the two methods suggest also that the semi-cylindrical load platens and neoprene sheets designed to apply the uni-directional stresses to the cylindrical rock specimen and test hole are appropriate.

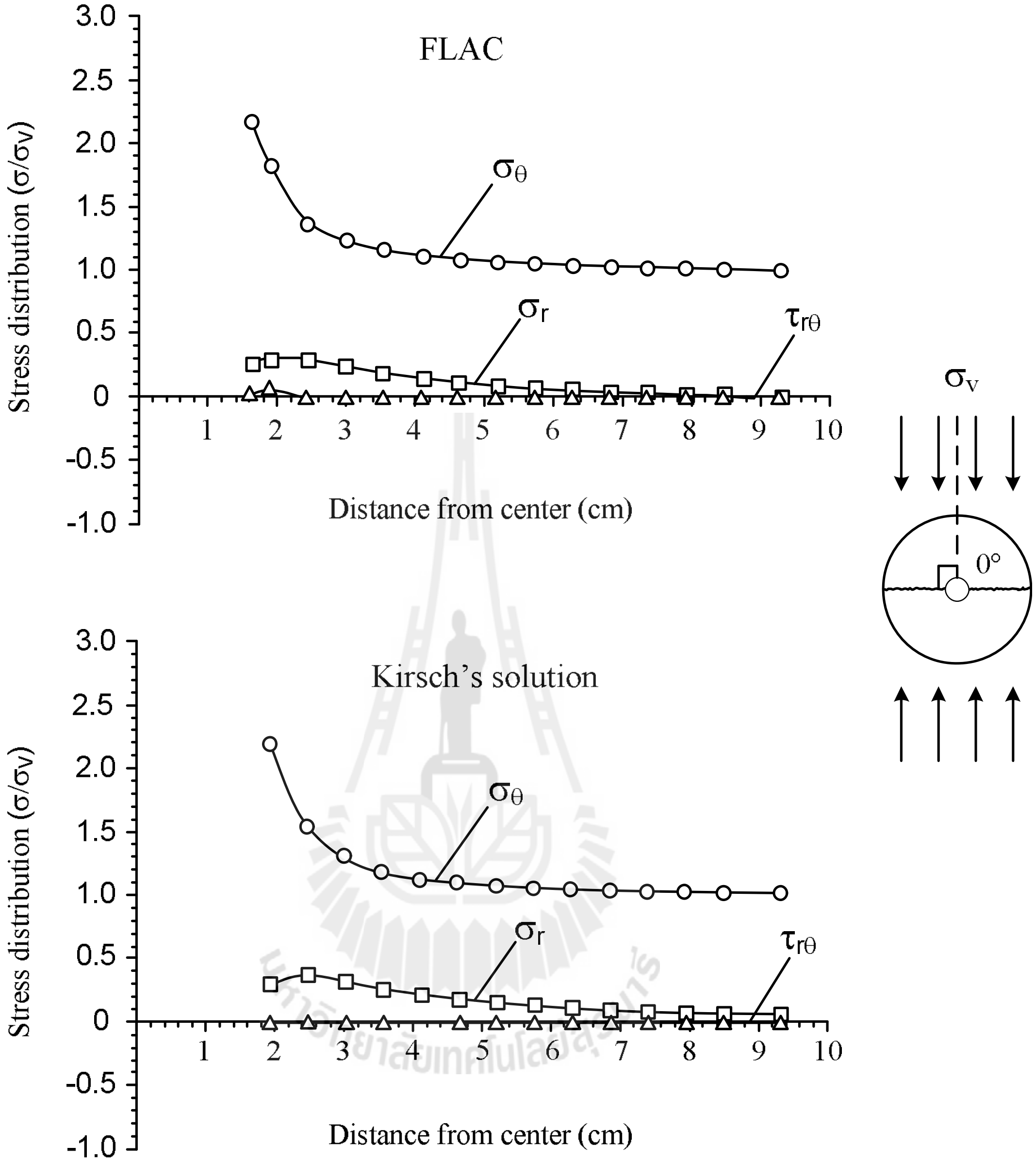

Figure 5.2 Comparison of the stress distributions between FLAC and Kirsch's solution for $\sigma_v = 1.85$ MPa and $\theta = 0$.

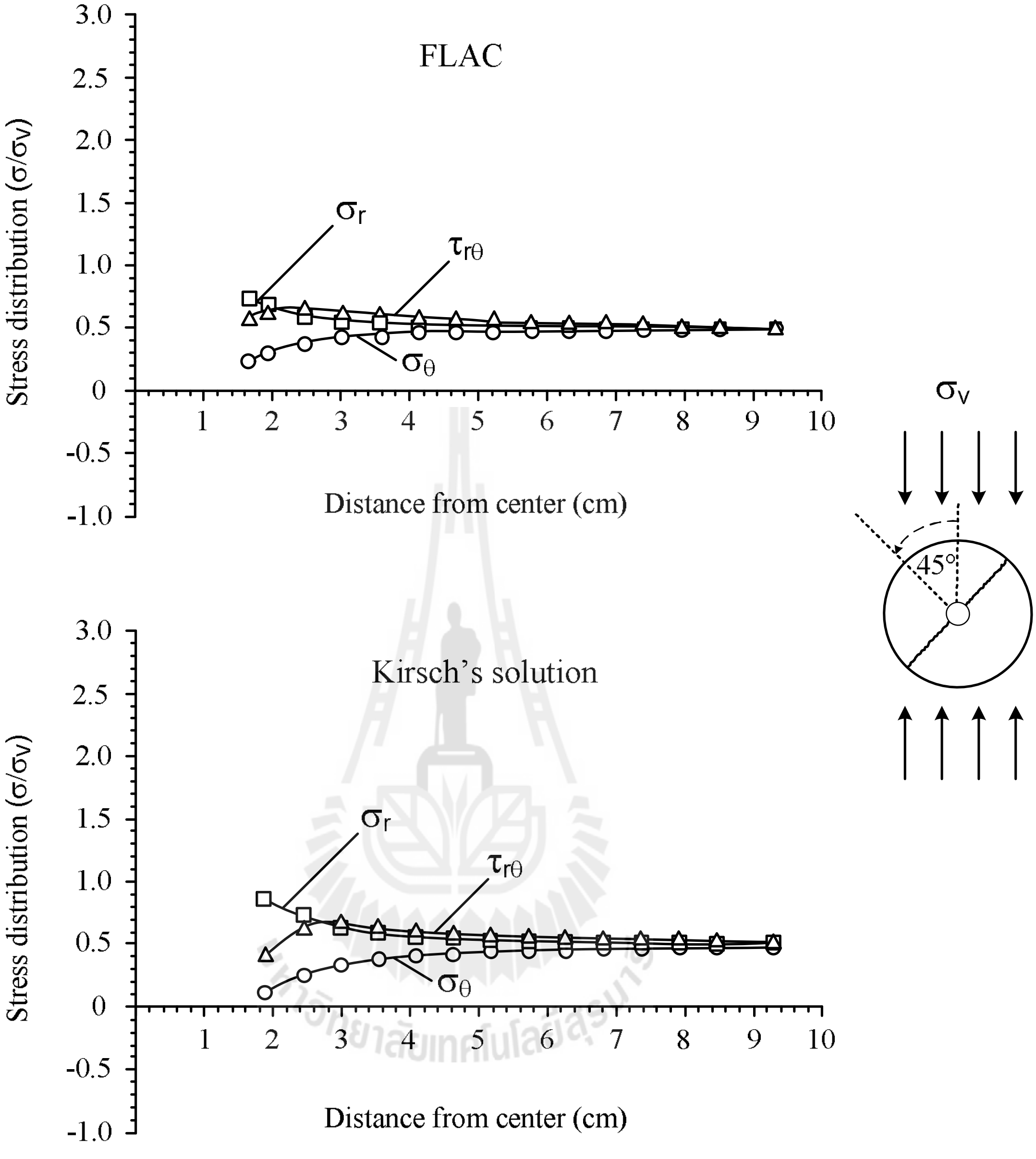

Figure 5.3 Comparison of the stress distributions between FLAC and Kirsch's solution for $\sigma_v = 1.85$ MPa and $\theta = 45°$.

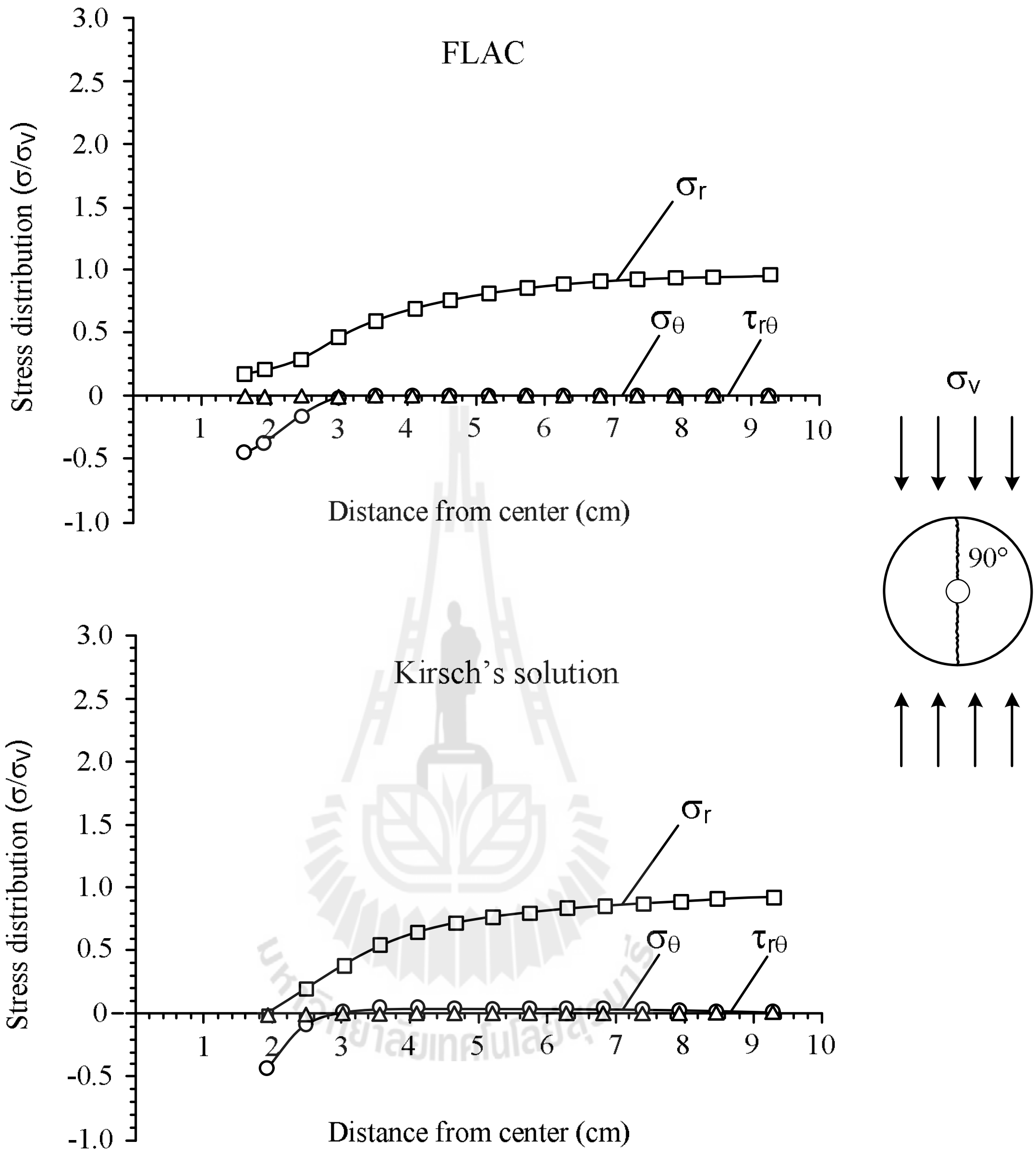

Figure 5.4 Comparison of the stress distributions between FLAC and Kirsch's solution for σ_v = 1.85 MPa and θ = 90°.

CHAPTER VI

DISCUSSIONS AND CONCLUSIONS

6.1 Discussions and conclusions

The results from the constant head flow tests on radial fracture under a variety of vertical stresses indicate that fracture permeability decrease with increasing normal stresses. This agrees with the experimental results by Xiao et al. (1999), Pyrak-Noltea and Morrisa (2000), Niemi et al. (1997), Indraratna and Ranjith (2001), Baghbanan and Jing (2008) and Akkrachattrarat et al. (2009). The apertures and permeability of rock fractures are also affected by the shearing displacement (Auradou et al., 2006).

The findings from this study clearly indicate that the normal stresses normal to the radial fracture can reduce the fracture permeability by up to one order of magnitude, depending on the magnitudes and orientations of the applied deviatoric and mean stresses. The fracture permeability can be increased if the shear stresses exist on the fracture plane. The permeability increase due to the shear stress is complicated by the fracture characteristics which probably involving asperity amplitudes and roughness, and hence difficult to interpreted. The joint shear and normal stiffness values probably are the key parameters that should be further investigated because they control the amount of aperture closure when the fractures are under stresses. Since only one rock type has been tested here, the effects of the joint stiffness and joint roughness coefficient cannot be examined.

The results from the close form solution agree well with there of the numerical analyzes while implies that the semi-cylindrical load frame can apply the shear and normal stresses on the fracture as designed. Observation from fracture permeability can be postulated that the permeability of radial fractures intersecting the borehole is in part governed by normal and shear stresses on the fracture plane. It has improved our understanding of fluid flow near the opening surrounding by fracture. A true understanding on complex stress on fracture plane is necessary for predicting the lost circulation of drilling mud or oil and gas lost from borehole or petroleum well.

6.2 Recommendations for future studies

The study in this research can be taken as a preliminary study. More laboratory testing should be performed using the higher confining pressures with larger specimens and different fracture roughness. The higher water injection pressures are needed to accelerate the test duration. The joint shear and normal stiffness values should be investigated. Laboratory testing would be improved by showing changes of fracture permeability with increasing stress on long term (more than 30 days).

REFFERENCES

Akkrachattrarat, N., Suanprom, P., Buaboocha, J. and Fuenkajorn, K. (2009). Flow testing of sandstone fractures under normal and shear stresses. In **Proceedings of the Second Thailand Symposium on Rock Mechanics.** Chonburi. Thailand. pp. 319-334.

Auradou, A., Drazer, G., Boschan, A., Hulin, J.P. and Koplik, J. (2006). Flow channeling in a single fracture induced by shear displacement. **Geothermics**. 35(5-6): 576–588.

Baghbanan, A. and Jing, L. (2006). Hydraulic properties of fractured rock masses with correlated fracture length and aperture. **International Journal of Rock Mechanics and Mining Sciences**. 44 (5): 704–719.

Baghbanan, A. and Jing, L. (2008). Stress effects on permeability in a fractured rock mass with correlated fracture length and aperture. **International Journal of Rock Mechanics and Mining Sciences** 45(8): 1320-1334.

Bandis, S. C., Barton, N. R., and Christianson, M. (1985). Application of a New Numerical Model of Joint Behavior to Rock Mechanics Problems. **Proceedings of the International Symposium on Fundamentals of Rock Joints**, Bjorkliden.

Bandis, S. C., Lumsden, A. C., and Barton, N. R. (1983). Fundamentals of rock joint deformation. **International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts**. 20: 249-268.

Brady, B. H. G. and Brown, E. T. (1985). **Rock Mechanics for Underground Mining** London: Chapman & Hall.

Detoumay, E. (1980). Hydraulic Conductivity of Closed Rock Fractures: An Experimental and Analytical Study. **Proceedings of the 13th Canadian Rock Mechanics Symposium** (pp 168-173). Toronto: (n.p.).

Gale, G. E. (1975). **A Numerical, Field and Laboratory Study of Fluid Flow in Rocks with Deformable Fractures**. Ph.D. thesis, University of California, Berkeley.

Gangi, A. F. (1978). Variation of Whole and Fractured Porous Rocks Permeability with Confining Pressure. **International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts**. 15: 249-257.

Gere, J.M. and Timoshenko, S. P. (1997) **Mechanics of materials** (4th ed.). Boston: PWS Pub Co.

Hoek, E. and Brown, E.T. (1990). **Underground excavations in rock.** London. UK. Institution of Mining and Metallurgy. pp. 102-106.

Indraratna, B., and Ranjith, P. (2001). **Hydromechanical Aspects and Unsaturated Flow in Joints Rock.** Lisse: A. A. Balkema.

Itasca (1992). **User Manual for FLAC–fast langrangian analysis of continua, version 4.0.** Itasca Consulting Group Inc. Minneapolis, Minnesota.

Iwai, K. (1976). **Fundamental Studies of Fluid Flow Through a Single Fracture**. Ph.D. thesis, University of California, Berkeley.

Jaeger, J. C., Cook, N. G. W., and Zimmerman, R. W. (2007). **Fundamentals of Rock Mechanics** (4th ed.). London: Chapman & Hall.

Kranz, R. L., Frankel, A. D., Engelder, T., and Scholz, C. H. (1979). The Permeability of Whole and Jointed Barre Granite. **International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts**. 16: 225-334.

Lawn, B. R., and Wilshaw, T. R. (1975). **Fracture of Brittle Solids**. Cambridge: Cambridge University Press.

Lee, C.H., and Farmer, I. (1993). **Fluid Flow in Discontinuities Rocks**. London: Chapman & Hall.

Makurat, A., Barton, N., Rad, N. S., and Bandis, S. (1990). Joint conductivity variation due to normal and shear deformation. **Rock Joints**, In Barton, N. S. and Stephansson, eds., Balkema, pp. 535-540.

National Research Council. (1996). **Rock Fractures and Fluid Flow: Contemporary Understanding and Applications**. Washington, D.C.: National Academy Press.

Nelson, R. (1975). **Fracture Permeability in Porous Reservoirs: Experimental and Field Approach**. Ph.D. dissertation, Department of Geology, Texas A&M University.

Niemi, A.P., Vaittinen, T.A., Vuopio, J.A. and Polla, J.P. (1997). Simulation of heterogeneous flow in a natural fracture under varying normal stress. **International Journal of Rock Mechanics and Mining Sciences** 34(3-4): 565.

Pyrak-Noltea, L.J. and Morrisa, J.P. (2000). Single fractures under normal stress: The relation between fracture specific stiffness and fluid flow. **International Journal of Rock Mechanics and Mining Sciences** 37(1): 245-262.

Ranjith, P. G. (2000). **Analytical and Numerical Investigation of Water and Air Flow Through Rock Media**. Ph.D. thesis, Department of Civil Engineering, University of Wollongong, Australia.

Ranjith, P. G. and Viete, D. R. (2011). Applicability of the 'cubic law' for non-Darcian fracture flow. **Journal of Petroleum Science and Engineering** 78(2): 321-327.

Singh, A. B., (1997). Study of Rock Fracture by Permeability Method**. Journal of Geotechnical and Geoenvironmental Engineering.** 123(7): 601-608.

Snow, D. T. (1970). The frequency and apertures of fractures in rock. **International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts**. 7: 23-40.

Suanprom, P., Obcheoy, J., and Fuenkajorn, K. (2009). Permeability of rock fractures under shear stresses. **EIT-JSCE Joint International Symposium Geotechnical Infrastructure Asset Management**, Bangkok. Thailand.

Tsang, Y. W. (1992). Usage of equivalent apertures for rock fractures as derived From hydraulic and tracer tests. **Water Resour. Res.**, 28(5): 1451-1455.

Walsri, C., Poonprakon, P., Thosuwan, R. and Fuenkajorn, K. (2009). Compressive and tensile strengths of sandstones under true triaxial stresses. In **Proceedings of the Second Thailand Symposium on Rock Mechanics.** Chonburi. Thailand. pp. 199-218.

Xiao, Y.X., Lee, C.F. and Wang, S.J. (1999). Assessment of an equivalent porous medium for coupled stress and fluid flow in fractured rock. **International Journal of Rock Mechanics and Mining Sciences** 36(7): 871-881.

APPENDIX A

PUBLICATION

Publication

Lertsuriyakul, C., Tepnarong, P. and Fuenkajorn, K., 2012, **Effects of normal and shear stresses on permeability of radial fractures around borehole.** In Proceeding of 7th Asian Rock Mechanics Symposium – ARMS 2012, Seoul, South Korea, 15-19 October 2012. (Published in electronic book. (http://www.docuhut.com/mydocuhut /fileroot//media/129/129357/media/default1.html)).

>> 2012 ARMS7 - 7th Asian Rock Mechanics Symposium
Seoul, South Korea, October 15-19, 2012

Effects of Normal and Shear Stresses on Permeability of Radial Fractures around Borehole

C. Lertsuriyakul[a*], P. Tepnarong[b] and K. Fuenkajorn[c]

[a] Graduate Stusent, [b]Instructor,[c]Associate Professor,
Geomechanics Research Unit, Suranaree University of Technology, Thailand
[*]Corresponding Author's E-mail: lertsuriyakul@hotmail.com

ABSTRACT

Laboratory flow tests have been performed to assess the effects of normal and shear stresses on the permeability of radial fractures around borehole. The rock specimens are prepared from Phu Kradung sandstone to obtain hollow cylinders having outside and inside diameters of 18.6 and 3.3 cm with a length of 15 cm. The rock is uniform and effectively impermeable. A radial fracture is artificially made by tension inducing method. It cuts through the borehole axis and along the specimen diameter. After applying a constant diametrical loading, the water is injectedunder constant head into the center hole. The fracture permeability is determined for various fracture orientations with respect to the vertical loading direction with 15° apart. The flow tests arerepeated 3 times under each vertical load to assess the permanent closure of the fracture under loading. The diametrical loads are progressively increased from 0.63MPa to 1.85MPa. Finite difference analyses have been performed to calculate the normal and shear stress distributions on the fracture under various orientations. The results indicate that the increases of the normal stresses rapidly decrease the fracture permeability.When the normal of fracture is deviated from the loading direction, the shear stress can increase the fracture permeability. A permanent closure of the fracture is observed as evidenced by the permanent reduction of the fracture permeability measured from the second and third cycles. The changes of aperture, water flow rate, and applied are used to calculate the changes of the fracture permeability. The fracture permeability is in the range between 1×10^{-18} m^2 and 1.5×10^{-15} m^2.

Keywords: Fracture, Permeability, Aperture,Borehole, Flow test

1. INTRODUCTION

It has been difficult to predict the groundwater inundation and loss of drilling fluid in complex hydro-geological environments prevailing in boreholes and petroleum wells. This is primarily because of the lack of proper understanding of flow through porous media containing systems of fractures. Fluid flow through rock mass is normally complicated by the presence of fracture systems which represent the dominant flow path. Fracture apertures and hydraulic conductivity are the main factors governing the rock mass permeability. Xiao et al. (1999), Pyrak-Noltea and Morrisa (2000), Niemi et al. (1997), Indraratna and Ranjith (2001), Baghbanan and Jing (2008) and Akkrachattrarat et al. (2009) conclude from their experimental results that fracture permeability exponentially decreases with increasing normal stresses. The apertures and permeability of rock fractures are also affected by the shearing displacement (Auradou et al., 2006). The fracture flow measurements in the field also complicated by the local stress induced by the test hole. Knowledge and understanding of fluid flow near the openings surrounding by fractures are rare.

The objective of this study is to experimentally assess how the normal and shear stress around the test borehole can affect the permeability of the radial fracture. The effort includes conducting flow tests under constant head and performing finite difference analysis.

2. ROCK SAMPLE

Phu Kradung sandstone has been selected for use as rock sample here primarily because it has highly uniform texture, density and effectively impermeable. It is classified as fine-grained quartz sandstone with 48.8% quartz (0.1-1.5 mm), 46.10% albite (0.1-0.8 mm), 5.1% kaolinite (0.1-0.3 mm), 3% rock fragments (0.5-2mm), and 2% others (0.5-1 mm). The average density is 2.63 g/cc. The cylindrical shaped specimen is 18.5 cm in diameter and 15 cm in length. A3.3 cm diametercenter hole is drilled along the specimen axis. The fracture are artificially made by tension inducing method. The fracture area is 18.5 × 15 cm. The joint roughness coefficient (JRC) of the test fractures is about 6-8.Figure 1 shows some rock specimens after the fracture has been induced.

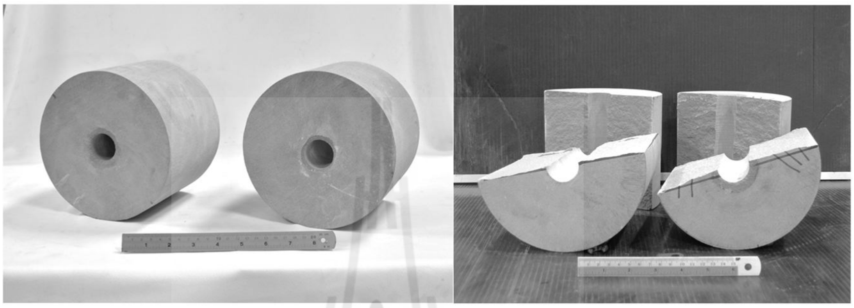

Figure 1. Some rock specimens prepared for constant head flow test (left). Tension-induced fracture along the diameter (right).

3. TEST METHOD

Constant head flow test is conducted by injecting water into the center hole. The laboratory arrangement while the fracture is under vertical stress is shown in Figure 2. The injected water pressure is41.4 kPa applied by a water pumpto oneend of the ceneter hole. The other end is plugged.The water pressure is maintained constant by using a regulating valve at the top of nitrogen gas tank of which connected to an acrylic tube to measure the inflow rate of water. The specimen is placed in a pair of semi-cylindrical load frames to apply vertical stress perpendicular to the specimen axis. Neoprene sheets are placed between the loading platens and the rock surfaces to minimize the friction. This load configuration imposes an anisotropic stress to the rock and fracture around test hole. The fracture permeability is determined for various orientations with 15°apart with respect to the loading direction,as shown in Figure 3. The vertical stresses are then progressively increased from 0.63, 1.24 to 1.85 MPa.The measured flow rates under each vertical load are used to calculate the fracture aperture and permeability. Assuming that the Darcy's law is valid, the equivalent cubic law is applied to determine the aperture (e_c) from the flow test results, as follows(Indraratna and Ranjith, 2001):

$$e_c = [[12q\mu] / [b(dp/dx)]]^{1/3} \quad (1)$$

where q is steady-state water flow rate (cm^2/s), μ is the dynamic viscosity of the water ($N{\cdot}s/cm^2$), b = width of the fracture (cm), dp/dx is the pressure gradient along the length of the specimen. The fracture permeability (k) can then be calculated by (Indraratna and Ranjith, 2001):

$$k = e^2/12 \quad (2)$$

where e is parallel plate aperture.The vertical stress (σ_v) is calculated by deviding the vertical load by the fracture area.

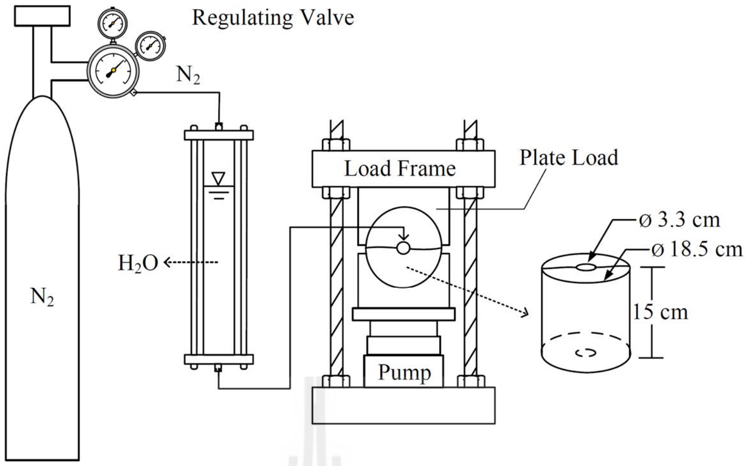

Figure 2. Laboratory arrangement for constant head flow test of radial fracture under vertical stress.

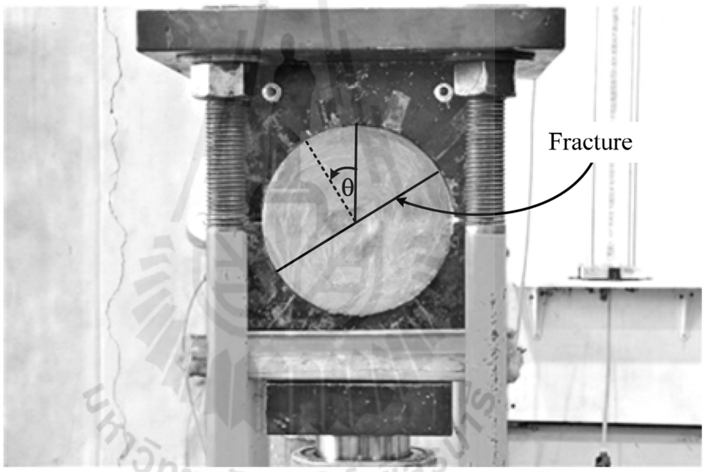

Figure 3. Cylindrical specimen can be rotated to obtain different normal and shear stresses on the tested radial fracture.

4. TEST RESULTS

The fracture permeability is calculated from the equivalent cubic law aperture. The results of some specimens are plotted as a function of fracture orientation in Figures4 and5. The fracture permeability varies as it rotates with respect to the loading direction. A permanent closure of the fracture under loading is observed as evidenced by the permanent reduction of the fracture permeability measured from the second and third cycles of testing. The fracture permeability decreases as the applied stresses increase. Increasing the vertical stresses from 0.63 MPa to 1.85 MPa can reduce the permeability by up to one order of magnitude.It is believed that the permeability variation with the fracture rotation is primarily due to the combined effects of the normal (tangential) and shear stresses induced on the fracture plane, providing that the radial stress has no effect on the fracture closure. More discussions on the issue are given below.

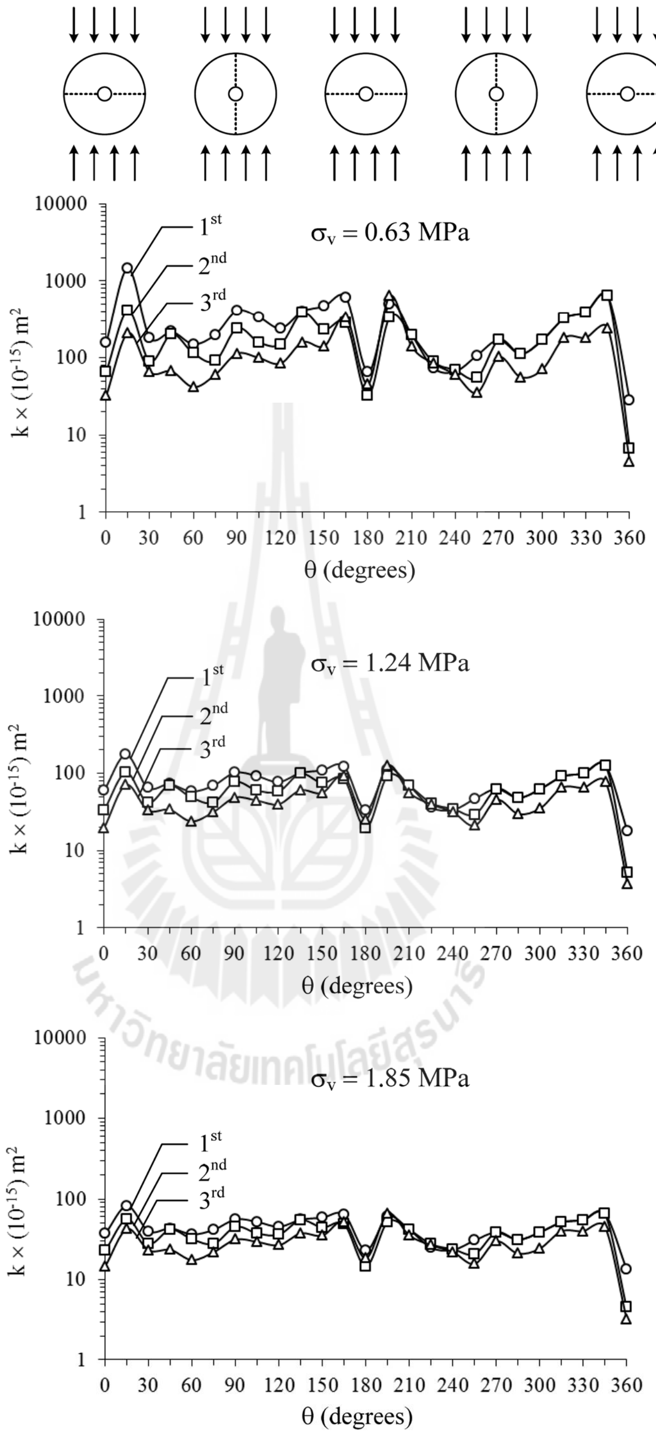

Figure 4. Fracture permeability as a function of fracture orientation for sample PKSS-01.

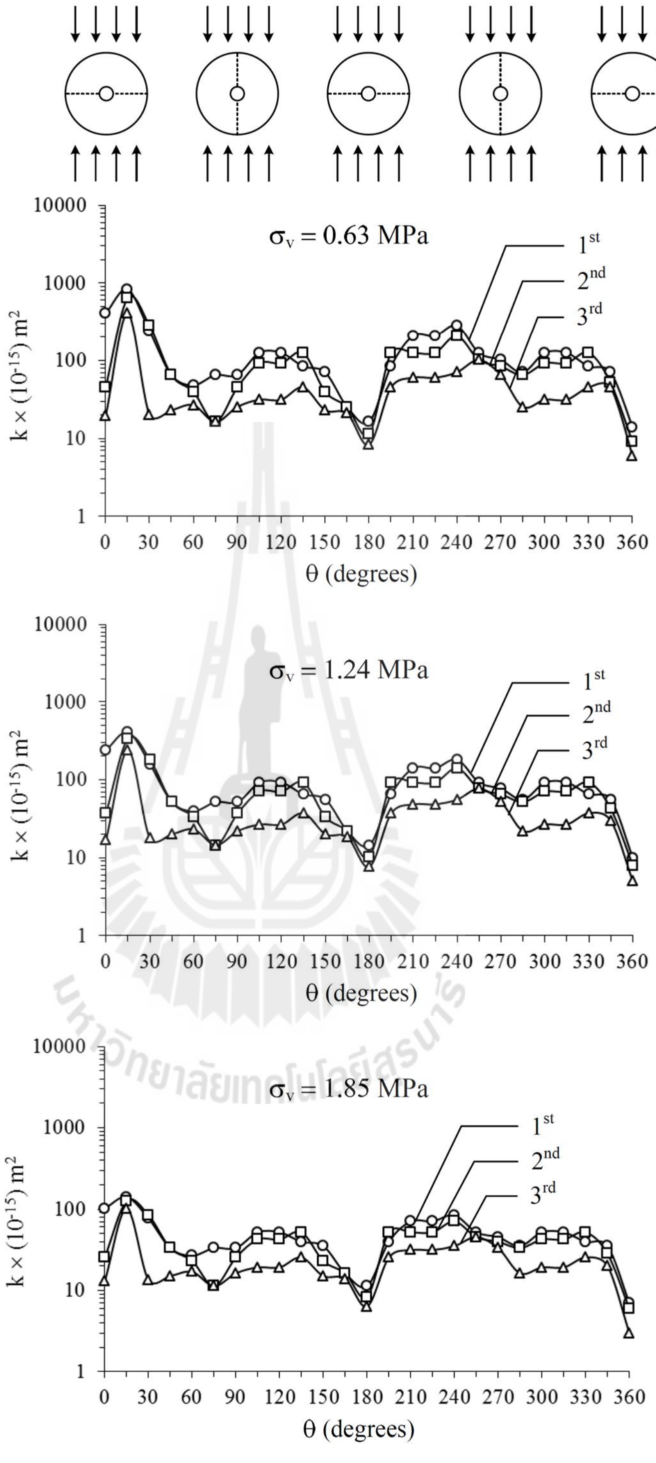

Figure 5. Fracture permeability as a function of fracture orientation for sample PKSS-02.

5. FINITE DIFFERENCE ANALYSES

To understand how the normal, shear and radial stresses change with respect to the fracture orientation finite difference analyses are performed using FLAC (Itasca, 1992). Figure 6 shows the two-dimensional finite difference mesh representing the cross-section of the loading platens and rock specimen. The fracture in the model can be defined for different orientations with respect to the loading direction. The rock model has a density of 2,700 kg/m^3. The bulk modulus and shear modulus of the sandstone are determined byWalsri et al. (2009) as 0.38 and 19.3 GPa.The joint normal and shear stiffness values (K_n and K_s) for the fracture in thePhu Kradung sandstone are determined by Akkrachattraratet et al.(2009) as4.8 GPa/m and 11 GPa/m. The joint friction angle and cohesion used in the simulations are 50° and 19 MPa. They are obtained from the direct shear testing conducted by Akkrachattrarat et al.(2009). All simulations assume plane strain condition. Table 1 summarizes the mechanical properties used in the calculation.

The stress distributions around borehole (σ_r, σ_θ, $\tau_{r\theta}$) are also calculated by Kirsch'ssolution (Hoek and Brown, 1990) to compare the results with those of the simulation. Both methods showsimilar distributions for the normal (tangential), shear and radial stresses on the fracture plane. Figures7through9 compare the stresses obtained from the two methods for θ = 0, 45° and 90°. The stress results are normalized by the applied stress σ_v in the figures. The close agreements of the results obtained from the two methods suggest also that the semi-cylindrical load platens and neoprene sheets designed to apply the uni-directional stresses to the cylindrical rock specimen and test hole are appropriate.

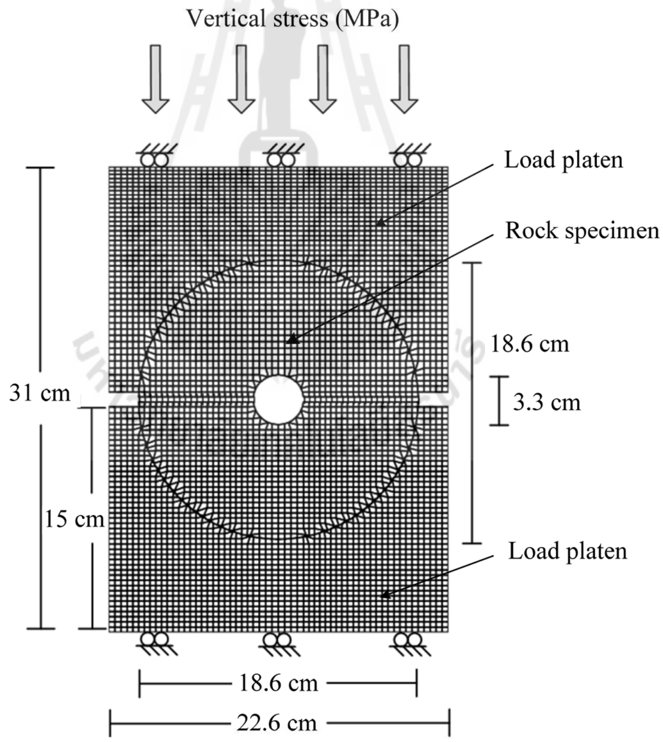

Figure 6. Finite difference mesh constructed to represent the test specimen and loading platens.

Table 1. Summary of the basic mechanical properties as obtained from Walsri et al. (2009).

Mechanical properties	PK sandstone	Steel
Density (kg/m^3)	2700	7750
Elastic Modulus (GPa)	7.7	200
Poisson's Ratio	0.38	0.3
Cohesion (MPa)	19	-
Tension (MPa)	8.7	-
InternalFriction Angle (degrees)	50	-
Dilation Angle (degrees)	25	-

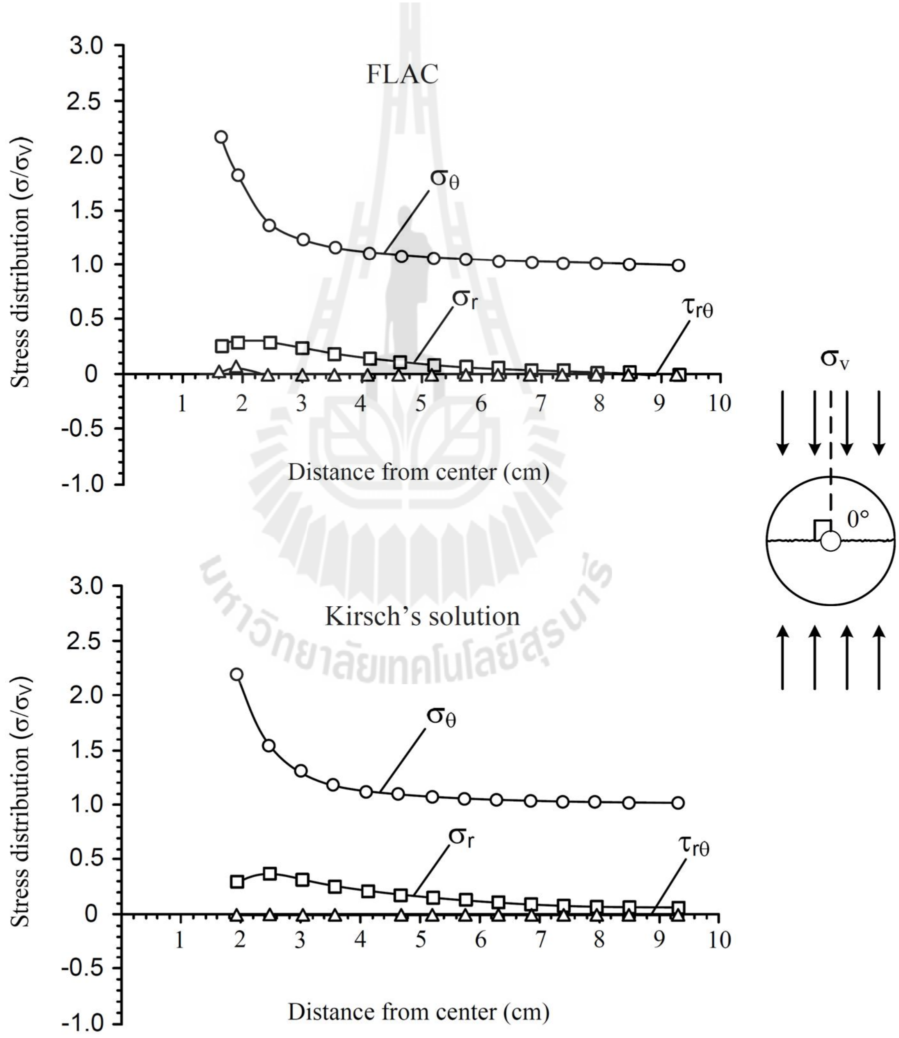

Figure 7. Comparison of the stress distributions between FLAC and Kirsch's solution for σ_v = 1.85 MPa and θ = 0.

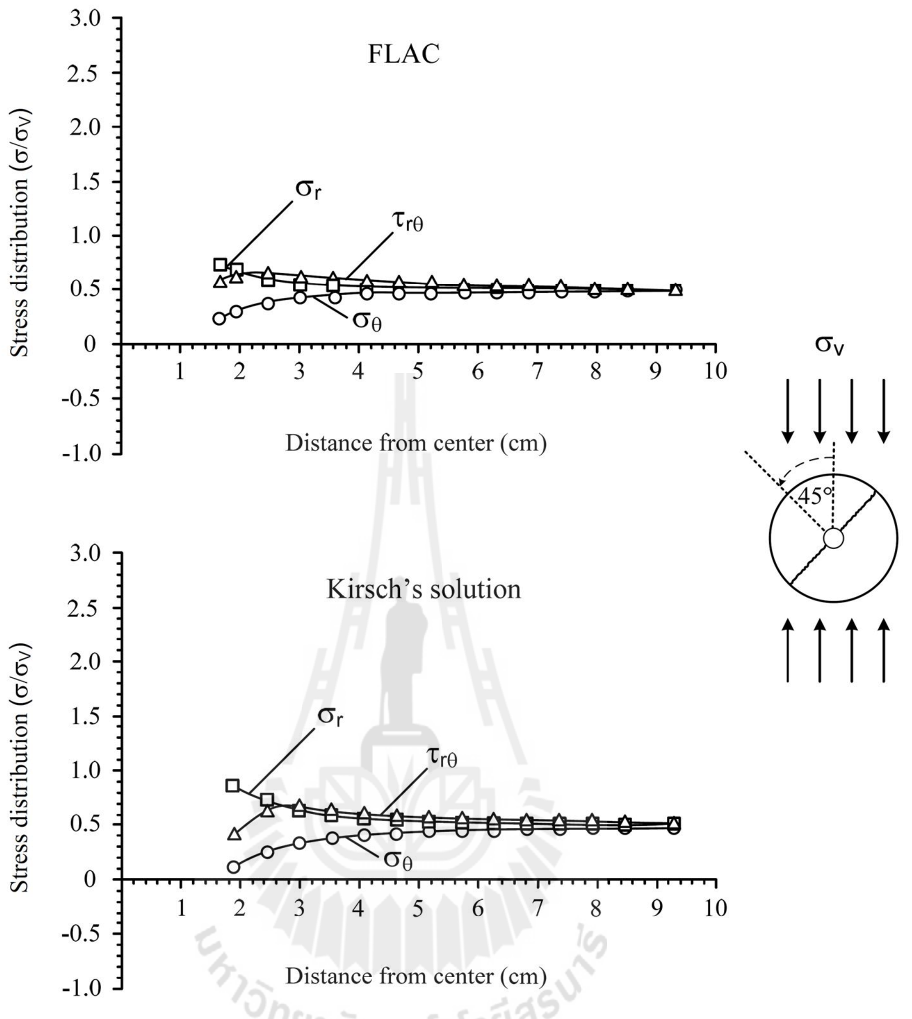

Figure 8. Comparison of the stress distributions between FLAC and Kirsch's solution for σ_v = 1.85 MPa and θ = 45°.

6. DISCUSSIONS AND CONCLUSIONS

The flow test results from different test cyclesshow parallel patterns of the permeability which indicate that the test procedure and results are repeatable and that the permeability variations are due to the nature of the fracture flow under rock stresses not due to the method of measurements. It can be postulated that the permeability of radial fractures intersecting the borehole is in part governed by the normal and shear stresses on the fracture plane. The permeability tends to be low when the fracture plane is normal to the loading direction (θ = 0 and 180°, maximum normal stress), and high when it is parallel to the loading direction (θ = 90° and 270°, minimum normal stress). If only normal stresses are considered the fracture permeability should decreases from its maximum values at θ = 0 and 180° to its minimum values at θ = 90° and 270°. Under these orientations the shear stresses are zero and have no effect on the permeability.

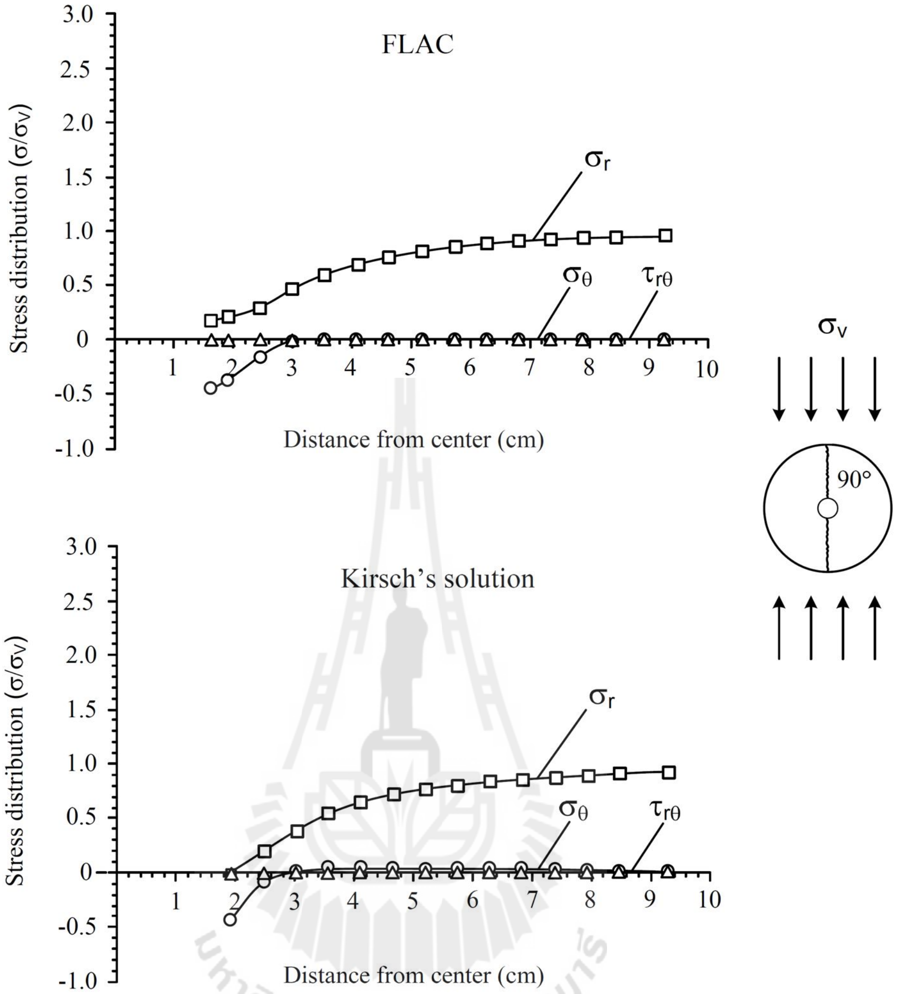

Figure 9. Comparison of the stress distributions between FLAC and Kirsch's solution for σ_v = 1.85 MPa and θ = 90°.

When the fracture deviates from the above orientations however the shear stresses start to have influence on the flow rate. The effect of the shear stress on fracture permeability is complicated by the roughness and asperity amplitude of the fracture which is not easy to interpreted. Nevertheless it seems that the shear stresses can increase the permeability magnitudes to be higher than those under no shear condition for both θ = 0 and θ = 90°. This postulation is based on assumptions that the rock specimen is effectively impermeable and that the radial stress (that parallel to the fracture plane) have no effect on the fracture flow.

The findings from this study clearly indicate that thetangential stresses normal to the radial fracture can reduce the fracture permeability by up to one order of magnitude, depending on the magnitudes and orientations of the applied deviatoric and mean stresses. The fracture permeability can be increased if the the shear stresses exist on the fracture plane. The permeability increase due to the shear stress is complicated by the fracture characteristics which probably involving asperity amplitudes and roughness, and hence difficult to interpreted. The joint shear and normal stiffness values probably are the key parameters that should be further investigated because they control the amount of aperture closure when the fractures are under stresses. Since only one rock type has been tested here, the effects of the joint stiffness values can not be examined.

ACKNOWLEDGEMENT

This study is funded by Suranaree University of Technologyand by the Higher Education Promotion and National Research University of Thailand. Permission to publish this paper is gratefully acknowledged.

REFERENCES

Akkrachattrarat, N., Suanprom, P., Buaboocha, J., Fuenkajorn, K., 2009, Flow testing of sandstone fractures under normal and shear stresses, *Proceedings of the Second Thailand Rock Mechanics Symposium*, 319-334.

Auradou, A.,Drazer, G., Boschan,A.,Hulin, J.P., Koplik,J.,2006,Flow channeling in a single fracture induced by shear displacement, *Geothermics*, 35, 576–588.

Baghbanan, A., Jing, L., 2008, Stress effects on permeability in a fractured rock mass with correlated fracture length and aperture,*International Journal of Rock Mechanics & Mining Sciences*,45, 1320-1334.

Hoek, E., Brown, E.T., 1990,*Underground excavations in rock*, London, Institution of Mining and Metallurgy, 102-106.

Indraratna, B., and Ranjith, P., 2001, *Hydromechanical aspects and unsaturated flow in joints rock*, A.A. Balkema, 96-105.

Itasca 1992a, FLAC–fast langrangian analysis of continua, version 4.0, user Manual, Itasca Consulting Group Inc.

Itasca 1992b, *User manual for FLAC–fast langrangian analysis of continua*, version 4.0, Itasca Consulting Group Inc.

Jaeger, J.C., Cook, N.G.W., 1979, *Fundamentals of rock mechanics (3rd ed.)*, Chapman & Hall,593.

Niemi, A.P., Vaittinen, T.A., Vuopio, J.A., Polla, J.P., 1997, Simulation of heterogeneous flow in a natural fracture under varying normal stress, *International of Rock Mechanics and Mining Sciences*,34, 565.

Pyrak-Noltea, L.J., Morrisa, J.P., 2000, Single fractures under normal stress: The relation between fracture specific stiffness and fluid flow, *International Journal of Rock Mechanics and Mining Sciences*, 37, 245-262.

Suanprom, P., Obcheoy, J., Fuenkajorn, K., 2009, Permeability of rock fractures under shear stresses, *EIT-JSCE Joint International Symposium Geotechnical Infrastructure Asset Management.*

Walsri, C., Poonprakon, P., Thosuwan, R., and Fuenkajorn, K., 2009, Compressive and tensile strengths of sandstones under true triaxial stresses, *Proceedings of the Second Thailand Symposium on Rock Mechanics*, 2, 199-218.

Xiao, Y.X., Lee, C.F., Wang, S.J., 1999, Assessment of an equivalent porous medium for coupled stress and fluid flow in fractured rock, *International of Rock Mechanics and Mining Sciences*, 36, 871-881.

BIOGRAPHY

Mr. Chanodom Lertsuriyakul was born on September 22, 1988 in Nakhon Ratchasima province, Thailand. He received his Bachelor's Degree in Engineering (Geotechnology) from Suranaree University of Technology in 2009. For his post-graduate, he continued to study with a Master's degree in the Geological Engineering Program, Institute of Engineering, Suranaree university of Technology. During graduation, 2009-2012, he was a part time worker in position of research assistant at the Geomechanics Research Unit, Institute of Engineering, Suranaree University of Technology. He published technical paper related to rock mechanics, titled "Effects of Normal and Shear Stresses on Permeabilityof Radial Fractures around Borehole" in the Proceedings of the 7th Asian Rock Mechanics Symposium, Seoul, South Korea.