

**ANISOTROPIC SHEAR BEHAVIOR OF JOINTED ROCK MASSES AT
ULU JELAI HYDROELECTRIC PROJECT, PAHANG**

by

NUR KHAFIZA SAPARI

**Thesis submitted in fulfilment of the
requirements for the degree of
Master of Science**

September 2018

ACKNOWLEDGEMENT

This Master's Degree work was initiated by the several researchers on Ulu Jelai Hydroelectric project. This study would not have been possible without data provided by Tenaga Nasional Berhad (TNB), SMEC Malaysia and Salini Impregilo and also the main financial support which is Research University Grant.

I am deeply thankful to my supervisor Dr. Hareyani Zabidi for inspiration, encouragement, supports, guidance and patiently reading and give positive comment on my numerous drafts along this journey. I would not complete this program without her positive vibes and trust. Thanks to some lecturers and staff at School of Material and Minerals Resources Engineering that always supports and providing guidelines along the way.

Special thanks to my parents, Sapari Yasir, Rupiah Tasrip and my parents in law for their involvement to give me moral supports, endless love and trust in everything I do. To my lovely and supporting husband, Muhammad Syamil Mohd Saad, thanks for always loving me. Thanks for your supports, positive vibes, loves and attention. I really hope we will grow old together. For my little Muhammad Syahid, thanks for accompany me while I am writing. Knowing you are here while everything seems so miserable made me realize that I need to keep moving and never give up. I pray to Allah to give you the best in your life here and hereafter.

This journey is so hard and seems to be impossible without so many persons involved in it. This short appreciation does not enough to express how gratitude am I having so much helps from them. Perhaps, this journey will never stop here.

TABLE OF CONTENTS

	Page
ACKNOWLEDGEMENT	ii
TABLE OF CONTENTS	iii
LIST OF TABLES	ix
LIST OF FIGURES	xii
LIST OF SYMBOLS	xv
LIST OF ABBREVIATIONS	xvi
ABSTRAK	xvii
ABSTRACT	xix
CHAPTER ONE : INTRODUCTION	
1.1 Problem Statement	1
1.2 Site Selection	4
1.2.1 Study Area	4
1.2.2 Project Detail	5
1.2.2(a) Site Investigation	10
1.3 Research Objectives	13
1.4 Research Approach	14
1.5 Thesis Outline	15

CHAPTER TWO : LITERATURE REVIEW

2.1	Introduction	17
2.2	Geology of Peninsular Malaysia	17
2.3	Major fault at Peninsular Malaysia	18
2.4	Anisotropy	23
2.4.1	Discontinuities in Relation to Anisotropic	25
2.4.2	Rock Mass Properties in Relation to Anisotropic	26
2.4.3	Strength Parameters of Anisotropic Rock	27
2.4.3(a)	In Situ Stress Analysis	27
2.4.3(b)	Review of Laboratory Analysis	29
2.5	Rock Mass Rating (RMR)	32
2.6	Summary	35

CHAPTER THREE : ULU JELAI HYDROELECTRIC PROJECT

3.1	Introduction	36
3.2	General Briefing	36
3.3	Susu Dam	38
3.4	General Tunnels and Underground Works	40
3.5	Basic Information of Study Area	43
3.5.1	General Geology	43
3.5.2	Geological Structure	45

3.5.3	Topography	46
3.5.4	Hydrogeology	49
3.5.5	Soils Condition	50
3.5.6	Groundwater Condition	52
3.6	Rock Discontinuity and Rock Mass Characterization of Study Area	53
3.6.1	General Consideration	53
3.6.2	Characterization of the Rock Material Components	54
3.6.3	Mylonitisation and Rock Mass Classification for Susu Dam	57
3.6.4	Characterization of Rock Discontinuities	57
3.7	Summary	59

CHAPTER FOUR : METHODOLOGY

4.1	Introduction	62
4.2	Field Study Analysis	63
4.2.1	Borehole Study	63
4.2.2	Geological Mapping	65
4.3	Analysis of Discontinuities Orientations	66
4.3.1	Stereographical Projection	66
4.3.2	Simulation	66
4.3.3	Procedure	66
4.4	Laboratory Analysis	68

4.4.1	Uniaxial Compressive Strength (UCS) Test	68
4.4.1(a)	UCS Test Objectives	68
4.4.1(b)	Sampling	69
4.4.1(c)	Sample Preparation	69
4.4.2	Indirect Tensile Strength (Brazilian) Tests	70
4.4.2(a)	Brazilian Test Objective	70
4.4.2(b)	Sampling	70
4.4.2(c)	Sample Preparation	71
4.5	In Situ Testing	71
4.5.1	Structural Analysis	71
4.5.1(a)	Boreholes Location and Features	71
4.5.1(b)	OPTV and BHTV Logging	73
4.5.1(c)	Equipment	74
4.5.1(d)	Data Processing	74
4.5.2	Stress Analysis	75
4.5.2(a)	Location and Background	76
4.5.2(b)	Reference Standards	77
4.5.2(c)	Testing Procedure	78
4.5.2(d)	Theoretical Background of HF	79
4.5.2(e)	Stress Calculation for HF	81

CHAPTER FIVE : RESULTS AND DISCUSSIONS

5.1	Introduction	84
5.2	Field Study Analysis	85
5.2.1	Borehole Study	85
5.2.2	Geological Mapping	89
5.3	Laboratory Testing	97
5.3.1	Uniaxial Compressive Strength (UCS) Test	97
5.3.1(a)	Summary Presentation of UCS Test Results	99
5.3.1(b)	Rock Mass Zoning Based on UCS Results	102
5.3.1(c)	Stress-strain Behavior and Elastic Moduli (E)	103
5.3.1(d)	Summary of Statistical Processing Data	106
5.3.2	Indirect Tensile Strength (Brazilian) Test	108
5.3.2(a)	Summary Presentation of BTS Test Results	110
5.4	In Situ Testing	112
5.4.1	Structural Analysis	112
5.4.1(a)	Results for CFZ01	113
5.4.1(b)	Results of DIL01	115
5.4.1(c)	Results of ISM01	117
5.4.1(d)	Results of ISM03	118
5.4.1(e)	Results of ISM04	120
5.4.1(f)	Results of ISM05	122
5.4.1(g)	Results of ISM06	124

5.4.1(h)	Data Correlations	125
5.4.2	Stress Analysis	129
5.4.2(a)	Detail Condition of Hydraulic Fracturing for Stress Analysis	131
5.4.2(b)	Results of Hydraulic Fracturing for Stress Analysis	134
5.4.2(c)	Correlation of Hydraulic Fracturing Results	138
5.5	Correlations of All Data Obtained	141
5.6	Relationship between Rock Mass Engineering Quality Developed by SMEC with Rock Mass Rating (RMR) System	145

CHAPTER SIX : CONCLUSIONS AND RECOMMENDATIONS

6.1	Conclusions	151
6.2	Recommendations	153

REFERENCES	155
-------------------	------------

APPENDICES

Appendix A: Example of geological mapping data

Appendix B: Total results of stereographical projection

Appendix C: Results for UCS test

LIST OF TABLES

		Page
Table 1.1	Summary of site investigation takes place at Ulu Jelai Hydroelectric project	10
Table 2.1	Topographic units based on mean elevations (Raj 2009)	18
Table 2.2	Rock Mass Rating (RMR) System (Beiniawski 1976)	34
Table 2.3	Guidelines for excavation and support of 10 m span rock tunnels in accordance with the RMR system (Beiniawski 1989)	35
Table 3.1	The typical soil profile (SMEC 1996)	51
Table 3.2	Rock material characterization outlined by SMEC	56
Table 3.3	Mylonitisation states and its acronym adopted by SMEC	57
Table 3.4	Classes of fracturing developed by SMEC	58
Table 3.5	Definitions of seepage rating according the engineering quality classes	58
Table 4.1	The summary of 7 boreholes location involved in this surveys program	72
Table 4.2	The main features of boreholes used for hydraulic tests	76
Table 5.1	Rosette diagram for the discontinuities orientations along the foundations dam	93
Table 5.2	Dominant orientation of the discontinuities along the Susu Dam	96
Table 5.3	Selected photographs of failed specimens during UCS test	101
Table 5.4	Range of UCS values according to different rock material	102

strength

Table 5.5	Value of E_t ranges for different rock mass class	105
Table 5.6	Summary of UCS results and E_t	107
Table 5.7	Data tabulation for BTS tests	110
Table 5.8	Summary results for BTS test	112
Table 5.9	Borehole features included for structural analysis program	112
Table 5.10	Summary results for CFZ01	114
Table 5.11	Summary results for DIL01	116
Table 5.12	Summary results for ISM01	118
Table 5.13	Summary results for ISM03	120
Table 5.14	Summary results for ISM04	121
Table 5.15	Summary results for ISM05	123
Table 5.16	Summary results for ISM06	125
Table 5.17	Summary data for structural analysis program	128
Table 5.18	Borehole features for hydraulic fracturing test (HF)	129
Table 5.19	Data tabulations for hydraulic fracturing test (HF)	134
Table 5.20	Hydraulic fracturing results using equation (4.3) and (4.4)	135
Table 5.21	Data correlation between field study analysis and laboratory analysis program	143
Table 5.22	RMR values based on rock mass engineering classes developed by SMEC	146

Table 5.23	Summary of the comparisons between rock mass engineering quality developed by SMEC and the RMR system by Beiniawski	149
------------	---	-----

LIST OF FIGURES

		Page
Figure 1.1	Ulu Jelai Hydroelectric project with adjacent reservoir and rivers	8
Figure 1.2	Aerial photo of Susu Dam (Poindexter 2016)	9
Figure 1.3	Borehole locations during site investigation phase along the Susu Dam	12
Figure 1.4	Sequential flowchart throughout the research.	14
Figure 2.1	A central spine of Peninsular Malaysia. The thin lines show the general structural grain and the thicker lines represent some major faults (Shuib 2009)	19
Figure 2.2	RADARSAT imagery of the Peninsular Malaysia shows the major lineaments that are interpreted as faults (Shuib 2009)	20
Figure 2.3	Interpretation of major lineaments as the major faults of the Peninsular Malaysia (Shuib 2009)	22
Figure 3.1	Layout for Ulu Jelai Hydroelectric project	37
Figure 3.2	Schematic diagram for Susu Dam area	38
Figure 3.3(a)	Downstream area of Susu Dam during constructions	39
Figure 3.3(b)	Upstream area of Susu Dam during constructions	39
Figure 3.3(c)	View from downstream area after water filling process	40
Figure 3.3(d)	View from upstream area after water filling process	40
Figure 3.3	Schematic diagram for some of the main component related to the Ulu Jelai Hydroelectric project	42

Figure 3.4	Rock mass engineering quality classes based on degree of fracturing and material states developed by SMEC (SMEC 1996)	59
Figure 4.1	Schematic diagram for the upstream of RCC dam to see the part that has been divided into 26 blocks and also the locations of fault zone area and the some of the boreholes drilled	64
Figure 4.2	Steps to add new file and insert new column according to the geological data involved	67
Figure 4.3	The example of analyzed data	68
Figure 4.4	Approximate locations of the samples collected for UCS test	69
Figure 4.5	Approximate locations of the samples collected for Brazilian test	70
Figure 4.6	Approximate locations of the borehole for the structural tests had been conducted	73
Figure 4.7	An example of data processing using WellCad software OPTV, BHTV and core box pictures are compared in function of depth	75
Figure 4.8	Approximate locations of the boreholes for the hydraulic fracturing	77
Figure 4.9	An actual record of test-interval pressure and flow rate versus time. This is the key point in pressure-time diagram (Haimson & Cornet 2003b)	80
Figure 5.1	The locations of 14 boreholes drilled along the foundation dam	86
Figure 5.2	Photo of rock cores for borehole BHD01	88
Figure 5.3	Photo of rock cores for borehole BHD06	89

Figure 5.4	Graph of frequency of discontinuities according to different block along the Susu Dam	90
Figure 5.5	Overlay of discontinuities distribution along the Susu dam with the location of drilling hole	91
Figure 5.6	Orientation pattern of the Rosette diagrams of the discontinuities along the Susu Dam	95
Figure 5.7	Borehole locations for UCS test	98
Figure 5.8	Frequency distribution of UCS across the foundation zone	99
Figure 5.9	Stress-strain curves in uniaxial compression test	103
Figure 5.10	Correlation of UCS with Young's Modulus (E)	106
Figure 5.11	Summary of the value for UCS and E according to different rock material component	107
Figure 5.12	Borehole locations for BTS tests	109
Figure 5.13	Frequency distributions of BTS across foundation zone	111
Figure 5.14	Rosette diagram for the summary of discontinuities in structural analysis	126
Figure 5.15	Borehole locations for hydraulic fracturing tests (HF)	130
Figure 5.16	Stereographic projection for the discontinuities orientation during HF test	139
Figure 5.17	Comparisons between the orientations obtain during geological mapping program with the HF study	141
Figure 5.18	Comparisons of the stereographic projection of the discontinuities orientation for the geological mapping study, structural analysis and stress analysis program with the orientations pattern of Peninsular Malaysia	144

LIST OF SYMBOLS

Symbols	Explanations
σ_h	Fracture normal stress
σ_H	Maximum horizontal stress
σ_t	Indirect tensile strength
σ_v	Vertical stress
μ	Mean
E	Young's Modulus
E_t	Tangent modulus of elasticity
P_s	Shut-in pressure
P_b	Breakdown pressure
P_r	Reopening pressure
P_0	Initial pressure
S	Standard deviation
S_h	Minimum horizontal stress
T	Tensile strength

LIST OF ABBREVIATIONS

Abbreviations	Explanations
N	North
S	South
E	East
W	West
NW	North West
SE	South East
NE	North East
SW	South West
NNW	North North West
SSE	South South East
WNW	West North West
ESE	East South East
ENE	East North East
WSW	West South West
UCS	Uniaxial compressive strength
BTS	Brazilian tensile strength
OPTV	Optic televiewer
BHTV	Borehole televiewer
HF	Hydraulic fracturing
ISM	In situ stress measurement
CFZ	Central foundation zone
DIL	Dilatometric
RCC	Roller compacted concrete
ISRM	International Society for Rock Mechanic
HTPF	Hydraulic testing of pre-existing fractures
RMR	Rock Mass Rating

SIFAT RICIH ANISOTROPIK UNTUK JASAD BATUAN BERKEKAR DI PROJEK EMPANGAN HIDROELEKTRIK ULU JELAI, PAHANG

ABSTRAK

Sifat ricih anisotropik untuk jasad batuan berkekar adalah salah satu isu penting dalam bidang kejuruteraan terutamanya dalam bidang pembinaan dan pembangunan. Kajian ini tertumpu pada keadaan geologi, kekuatan batuan dan keadaan tegasan *in situ*. Kajian ini telah dijalankan di projek empangan hidroelektrik di Ulu Jelai, yang dibina berdekatan dengan Cameron Highland, Pahang. Satu empangan konkrit berpemadatan guling (RCC) dengan ketinggian 88 m telah dibina bersama 22 km terowong pengalihan sebagai sebahagian daripada struktur empangan. Jasad batuan di kawasan kajian adalah agak sukar untuk dikaji kerana siri serantau yang berulang dan ricih. Secara geologinya, Cameron Highland terdiri daripada lineamen BL, TL and US dan dipotong dengan arah BL, TL and US jika dilihat dari bukti pergerakan Cenozoic. Berdasarkan dari kajian lapangan terkini, sebahagian sesaran ini adalah bukti pergerakan Quaternary Pleistocene sehingga Holocene. Pada masa yang sama, arah sesaran utama Semenanjung Malaysia adalah terarah kepada U-S, UBL-STG, BL-TG, BBL-TTG, B-T, TTL-SBD dan TL-BD. Berdasarkan ujian kekuatan mampatan uniaxial (UCS) menunjukkan jumlah julat antara 0.5 – 96.0 MPa manakala ujian Brazilian (BTS) jumlah julat antara 0.5 – 14.31 MPa. Daripada ujian tegasan *in situ* pula menunjukkan rekahan yang terhasil di dalam lubang yang telah di gerudi dan rekahan yang dihasilkan semasa ujian hidraulik menunjukkan corak yang sama dengan corak sesaran utama di Semenanjung Malaysia. Magnitud dan arah rekahan juga telah ditentukan sewaktu kajian analisis di mana tegasan melintang maksimum adalah kira-kira 6 MPa yang mempunyai arah normal dari paksi empangan yang mempunyai nilai penghampiran 30° dan *pseudo* mendatar

mempunyai kekuatan kira-kira 4 MPa. Satu korelasi telah dibuat merujuk kepada data yang diperolehi di mana terdapat hubungan yang kuat antara orientasi regim tegasan utama di Susu Dam dengan corak sesaran utama di Semenanjung Malaysia. Korelasi antara kualiti jasad batuan yang diperkenalkan oleh SMEC dengan sistem Penilaian Jasad Batuan (RMR) yang diperkenalkan oleh Beiniawski juga telah ditentukan dalam kajian ini. Daripada pemerhatian, sistem yang dibuat oleh SMEC adalah terhad kepada tahap proses *mylonitisation* sahaja sementara sistem RMR adalah lebih umum dan boleh digunakan secara meluas untuk kebanyakan keadaan batuan.

ANISOTROPIC SHEAR BEHAVIOR OF JOINTED ROCK MASSES AT ULU JELAI HYDROELECTRIC PROJECT, PAHANG

ABSTRACT

The anisotropic shear behavior of jointed rock mass is one of the crucial issues in engineering field especially to the construction and developments. This research focused on the geological condition, rock mass strength and in situ stress state. The research has been done at Ulu Jelai Hydroelectric Dam project, which currently constructed near Cameron Highland, Pahang. An 88 m height of roller-compacted concrete (RCC) of dam is build with 22 km diversion tunnel as a part of dam structure. The rock mass is very difficult due to repeated regional series of faulting and shearing. Geologically, Cameron Highland is characterized by NW, NE and N-S lineaments and cut by NW, NE and N-S by going through faults displaying evidence for Cenozoic movements. Recent field investigation has identified that some of these faults evidence for Quaternary Pleistocene to Holocene movements. On the other hand, major faults in the Peninsular Malaysia strike at N-S, NNW-SSE, NW-SE, WNW-ESE, E-W, ENE-WSW and NE-SW. The value of uniaxial compressive strength (UCS) test is in the range of 0.5 – 96.0 MPa while the Brazilian Tensile Strength (BTS) test is about 0.5 – 14.31 MPa. The in situ stress analysis shows that the fractures occur in the borehole and the induced fractures during the hydraulic fracturing test follows the major fault pattern of Peninsular Malaysia. The magnitude and the direction of fracture have been determined during this analysis study which is the maximum horizontal stress has been found approximately 6 MPa with the direction normal to the dam axis with an approximation of $\pm 30^\circ$ and the least pseudo-horizontal has been found approximately 4 MPa. The correlation has been made referring to the data obtained where there is a strong relationship between the

orientations of principal stress regime at Susu Dam with the major fault pattern of Peninsular Malaysia. The correlation between the rock mass quality introduced by SMEC with the Rock Mass Rating (RMR) system introduced by Beiniawski also has been determined during this research. From the observation, the system developed by SMEC is limited to the degree mylonitisation while the RMR system is more general and can be widely used for any rock material conditions.

CHAPTER ONE

INTRODUCTION

1.1 Problem Statement

Shear behavior of jointed rock masses is one of the critical issues in rock engineering and a lot of research has been done to understand its concept especially when it related to construction such as stability of slopes and dam foundation. The importance to have extensive study at project site before construction is widely aware, but it always related to the high cost in relation to the test and the technical challenges in implementation make this study more challenging.

The shear behavior of jointed rock masses is commonly affected by the mechanical properties of intact rock and its geometrical characteristics of joint systems such as the orientations of the joint sets and direction of the shear loading. Different geometrical characteristics will cause different failure mechanisms (Li et al. 2014).

Before construction, it is important to study the rock mass behavior to give insight into the deformation behavior and failure mechanism of jointed rock masses. In-situ test are typically been conducted to get the detailed information but due to financial constraints and in-situ test are basically expensive, laboratory test can also be conducted.

In this study, the anisotropic shear behavior of jointed rock masses will be studied based on the Ulu Jelai Hydroelectric Dam project, which currently constructed near Cameron Highland, Pahang. An 88 m roller-compacted concrete

(RCC) dam is built with 22 km diversion tunnel as a part of the dam structure. The rock mass is expected to be very difficult due to repeated regional series of faulting and shearing. Geologically, Cameron Highland is characterized by NW, NE and N-S lineaments and cut by NW, NE and N-S by going through faults displaying evidence for Cenozoic movements. Recent remote sensing and field investigation have identified that some of these faults evidence for Quaternary Pleistocene to Holocene movements (Shuib 2009). Some short NW, NE and N-S faults along a major NE and ENE trending fault zone show abundant geomorphic, structural and stratigraphic evidences for late Quaternary activity.

On the other hand, major faults in the Peninsular Malaysia strike at N-S, NNW-SSE, NW-SE, WNW-ESE, E-W, ENE-WSW and NE-SW have undergone complex repeated movements and shearing, including microstructure evidence for both sinistral and dextral movements along many strike-slip faults (Shuib 2009). This deformation is observed as ductile shear zones, which are relatively long and narrow zones of relative displacement. These zones have the main characteristics such as large deformability, strong dependence of resistance on degree of saturation or temperature and susceptibility to alteration.

The Susu Dam site was investigated in 2003 and additional investigation have been carried out in 2011 and 2012 for detailed design. The investigation is carried out to have a better understanding of the Bertam Fault zone which was inferred to be located in the left abutment, but its precise location and characteristics were not known because only vertical boreholes had been drilled. The first challenge is to study the existing fractured network problem from the geological mapping at the dam foundation and correlate the information with regional geology of Peninsular

Malaysia. The other challenge is to study the characteristic of the Bertam Faults zone at the left abutment of the foundation because the stability of the RCC dam depending on the strength of its foundation itself and will this gives a potential problem in the dam foundation excavations.

The uniqueness of the study area is about the geology where during the preliminary study by SMEC, they found the fault zone and mylonised zone occur and it arise another question on the strength of the foundation. The mylonised granite has been so intensely sheared that it no longer resembles granite. It has been reconstituted into predominantly fine grain (silt and sand sized) weak rock that typically has a foliated or flow banded appearance. The granite has basically been ground to 'rock flour'. If broken apart it often reveals polished or slickensided surfaces. It is emphasized that no thick gouges appear to be associated with these mylonites. The uppermost 0.5 m of core recovered in the borehole is mylonite (at about 20 m), so the mylonite full width is not known. The study should be continued to see either there is intersection between the mylonite zone and fault zone or not because this information will gives an important explanation to understand the fracture network that occurs at the site and how this understanding can help in any analysis of the current stress field and also the imposed stress field of the dam.

Referring to various study on the strength variation of the anisotropic rock masses, no clear distinction can be made to conclude that the range of rock strength variation is same widely because the geological factors is deferent at different area. Based on research work on the in-situ test and laboratory test at the project site correlated with the geological condition, it really helps in terms of understanding rock strength variations and its characteristic of the anisotropic rock behavior. In this

case, the orientation of existing fracture networks in relation with regional stress and the mechanical properties need to be fully understood to see what is the significant of a locally determined stress measurement with relation to the regional stress field.

Generally, the objective of this research is to determine the orientation of principal stress regime and its relation to the major fault pattern of Peninsular Malaysia. For this purpose, the Susu Dam foundation is selected as a project area. Hence, this research will discuss about the geological discontinuities orientations correlated with rock mechanical properties and in-situ stress condition.

1.2 Site Selection

1.2.1 Study Area

Ulu Jelai Hydroelectric Project is developed by Tenaga Nasional Berhad (TNB) located in the state of Pahang, in the district of Cameron Highland. It is located about 140 km north of Kuala Lumpur.

The main features of the Ulu Jelai Hydroelectric Project comprise an 88 m high RCC dam called Susu Dam, two diversion weirs on Sungai Lemoi and Sungai Telom for the diversion of flows from adjacent catchment via 7.3 km and 8 km long transfer tunnels into Sungai Bertam, a 372 MW underground power station and the required associated water conveyance and access road system. The hydroelectric development will generate peaking energy to the national grid.

The first feasibility study has been done in 1988 and the study is continued until 2004. The Susu Dam site was investigated in 2003 and detailed surveys were done in a year of 2008. All investigation stages included seismic traverses and cored boreholes with water pressure testing. Acoustic televiewing was also carried out in