

GEOMECHANICAL MODEL FOR SURFACE EXCAVATION  
IN TROPICALLY WEATHERED GRANITE

SEYED VAHID ALAVI NEZHAD KHALIL ABAD

UNIVERSITI TEKNOLOGI MALAYSIA

GEOMECHANICAL MODEL FOR SURFACE EXCAVATION  
IN TROPICALLY WEATHERED GRANITE

SEYED VAHID ALAVI NEZHAD KHALIL ABAD

A thesis submitted in fulfilment of the  
requirements for the award of the degree of  
Doctor of Philosophy (Civil Engineering)

Faculty of Civil Engineering  
Universiti Teknologi Malaysia

JULY 2014

## **DEDICATION**

### **Specially Dedicated To...**

#### **My Beloved Father and Mother**

#### **My Brothers**

Thanks for all the love, support, motivation and always being there  
whenever I need you.

#### **My Supervisor**

Assoc. Prof. DR. Edy Tonnizam Bin Mohamad

For his guidance and assistance throughout the whole thesis.

## ACKNOWLEDGMENTS

First and foremost, gratitude and praises to Allah, The Most Gracious and The Most Merciful for his blessing in completing this thesis. Pursuing a Ph.D. thesis is a both painful and enjoyable experience. It is just like climbing a high peak, step by step, accompanied with bitterness, hardships, frustration, encouragement and trust and with so many people's kind help. When I found myself at the top enjoying the beautiful scenery, I realized that it was, in fact, teamwork that got me there. Though it will not be enough to express my gratitude in words to all those people who helped me, I would still like to give my many, many thanks to all these people.

First of all, I would like to express my sincere gratitude to my honorific supervisor Assoc. Prof. DR. Edy Tonnizam Bin Mohamad who accepted me as his Ph.D. student without any hesitation when I presented him my research proposal. I am extremely grateful for his continuous support in my Ph.D. study and research, patience, motivation, enthusiasm and immense knowledge. His guidance helped me in all the time of research and writing of this thesis. I have learned a lot from him, without his help I could not have finished my thesis successfully.

Special thanks are also given to my co-supervisors Prof. Emeritus Dato' DR. Ibrahim Bin Komoo and Assoc. Prof. Mohd For Bin Mohd Amin for their encouragement and insightful comments.

During my research, DR. Roohollah Kalatehjari offered me a lot of friendly help. I would like to give my sincere thanks to him for his encouragements and generous help. Also, I would like to express my appreciation to my dear friends Mr. Danial Jahed Armaghani and Mr. Mohammad Ridzuan Bin Jahidin for their kind encouragements and supports.

Last but not least, I am greatly indebted to my parents. Their love and support without any complaint or regret has enabled me to overcome all difficulties during my studies. I love you so much and you are my hero.

## ABSTRACT

Mass heterogeneity, abrupt changes in weathering state and presence of boulders in tropically weathered granite lead to uncertainties in predicting the surface excavation performance. This study proposed a new geomechanical model for prediction of surface excavation rate by considering the complex characteristics and effective parameters of weathered granite. Beside the new model, a typical mass weathering profile of granite was proposed with details of rock mass characteristics including typical appearance, discontinuities characteristics, shape and size of boulder, homogeneity and rock to soil ratio in each mass weathering grade. Based on extensive study of forty panels from four granite quarries, the effect of weathering on the mentioned parameters were established. Practical excavation was performed in excavable zones in the quarries. Statistical analysis using multiply linear regression was performed on the relation of the parameters and practical excavation rate to investigate effective parameters of rock mass and rock material in surface excavation. Then after, the correlation of each parameter with practical excavation rate was obtain utilizing Pearson Correlation Coefficient (PCC). Based on PCC and the results of laboratory tests and site investigation, a rating system in a chart know as Excavation Index in Granite (EIG) was proposed. EIG value was calculated for each weathering zone in each panel of the quarries. The correlation between the results of practical excavation and the values of EIG was obtain and then used to propose a chart of excavability classification in granite. The chart consists of excavation classes, the range of excavation rates and the excavability conditions. Finally, the applicability of the proposed model was verified by comparing the predicted ranges of surface excavation rate using the model and the results of practical excavation rate at another site. The proposed model contributes to the field of surface excavation in tropically weathered granite.

## ABSTRAK

Kerencaman massa batuan, perubahan tahap luluhawa serta kehadiran batu bundar (boulder) yang tidak menentu membuat penilaian kerja pengorekan adalah sukar di kawasan beriklim tropika. Kajian ini membangunkan model geomekanikal yang mampu meramal kadar pengorekan berdasarkan sifat massa batuan terluluhawa yang bersifat kompleks dan kadang kala mengelirukan. Di samping itu, profil luluhawa yang kebiasaannya dijumpai di kawasan tropika juga diusulkan dengan mengambil kira ciri ciri massa batuan, ketakselajaran, kerencaman massa batuan dan nisbah batuan kepada tanah untuk tahap luluhawa berbeza. Berdasarkan kajian terperinci empat puluh panel yang dikaji iaitu daripada empat buah kuari, kesan luluhawa terhadap parameter kejuruteraan telah dicadangkan. Ujikaji pengorekan sebenar telah dilaksanakan dalam zon luluhawa berbeza. Analisa statistik dengan menggunakan regresi linear berbilang dilakukan bagi mengkaji hubungan parameter batuan dan kadar pengorekan. Korelasi setiap parameter dengan kadar penggalian praktikal telah diperolehi menggunakan Pearson Correlation Coefficient (PCC). Berdasarkan PCC dan keputusan makmal serta kajian tapak, sistem pengelasan Excavation Index in Granite (EIG) telah dibangunkan. Sistem ini mengambil kira kategori penggalian, kadar dan situasi ketika kerja pengorekan dijalankan. Sebagai penilaian keupayaan model, ianya telah diuji dengan meramal kadar pengorekan model dengan keputusan sebenar di sebuah tapak berbeza. Dengan hasil kadar peramalan yang jitu, adalah dijangkakan model geomekanikal yang dicadangkan ini berupaya menyumbang kepada bidang pengorekan yang melibatkan batuan granit terluluhawa.

## TABLE OF CONTENTS

CHAPTER	TITLE	PAGE
	<b>DECLARATION</b>	ii
	<b>DEDICATION</b>	iii
	<b>ACKNOWLEDGMENTS</b>	iv
	<b>ABSTRACT</b>	v
	<b>ABSTRAK</b>	vi
	<b>TABLE OF CONTENTS</b>	vii
	<b>LIST OF TABLES</b>	xii
	<b>LIST OF FIGURES</b>	xvi
	<b>LIST OF ABBREVIATIONS</b>	xx
	<b>LIST OF APPENDICES</b>	xxi
<b>1</b>	<b>INTRODUCTION</b>	<b>1</b>
	1.1 Background	1
	1.2 Problem Statement	2
	1.3 Objectives of the Study	4
	1.4 Research Questions	4
	1.5 Scope and Limitations of the Study	5
	1.6 Significance of the Study	6
	1.7 Study Area	6
<b>2</b>	<b>LITERATURE REVIEW</b>	<b>8</b>
	2.1 Introduction	8
	2.2 Excavation Methods for Underground and Surface Excavation	10
	2.2.1 Drilling and Blasting	12
	2.2.2 Mechanical Excavation	13

	2.2.2.1	Mechanical Excavators in Surface Excavation	15
	2.2.2.2	Hydraulic Excavator	17
2.3		Rock Types	19
	2.3.1	Igneous Rock	21
	2.3.2	Sedimentary Rock	22
	2.3.3	Metamorphic Rock	23
2.4		Rock Mass Characteristics	24
	2.4.1	Tropical Weathering Process in Rock	27
	2.4.2	Rock Material Characteristics	31
	2.4.2.1	Physical Characteristics of Rock Material	32
	2.4.2.2	Mechanical Characteristics of Rock Material	34
	2.4.3	Discontinuities	36
	2.4.4	Boulders	42
	2.4.5	Homogeneity and Heterogeneity	43
2.6		Factors Influencing Surface Excavation	45
2.7		Rock Excavability Classifications	47
2.7		Rock Mass Classifications for General Applications	53
	2.7.1	The Rock Quality Designation (RQD)	57
	2.7.2	Rock Mass Rating (RMR)	58
	2.7.3	Modified Rock Mass Rating (M-RMR)	61
	2.7.4	Geological Strength Index (GSI)	63
	2.7.5	Application of Rock Mass Classification System in Weathered Rock	67
2.9		Development in Weathering Profile	69
<b>3</b>		<b>RESEARCH METHODOLOGY</b>	<b>74</b>
	3.1	Introduction	74
	3.2	Field Work	77
	3.2.1	Observation and Field Mapping	78
	3.2.2	Dividing Selected Rock Exposures into Panels	80
	3.2.3	Identification of Mass Weathering Grades	81



3.2.4	Determining Topography and Rock Mass Description	81
3.2.5	Discontinuity Characterization	82
3.2.6	Preparing Sketches of Mass Weathering Grades in Panels	83
3.2.7	In-situ Test	83
3.2.8	Collecting Samples for Laboratory Testing	83
3.4	Laboratory Testing	84
3.4.1	Petrographical Analysis	85
3.4.2	X-ray Diffraction Test	85
3.4.3	Dry Unit Weight Test	86
3.4.4	Water Absorption Test	87
3.4.5	Sonic Wave Velocity Test	87
3.4.6	Point Load Test	88
3.4.7	Indirect Tensile Strength (Brazilian) Test	89
3.4.8	Uniaxial Compressive Strength Test	90
3.4.9	Slake Durability Test	91
3.4	Geomechanical Model for Surface Excavation	93
3.5	Verification of the Model	96
<b>4</b>	<b>ROCK MASS CHARACTERIZATION</b>	<b>97</b>
4.1	Introduction	97
4.2	Field Mapping and Geological Characterization	97
4.2.1	Study of Rock Exposures in Segamat Quarry	109
4.2.1.1	Joint Spacing and Trace Length	109
4.2.1.2	Joint Orientation	110
4.2.1.3	Sketches of Panels	111
4.2.1.4	Summary of Rock Mass Characteristics	118
4.2.2	Study of Rock Exposures in Seri Alam Quarry	122
4.2.2.1	Joint Spacing and Trace Length	122
4.2.2.2	Joint Orientation	123
4.2.2.3	Sketches of Panels	124
4.2.2.4	Summary of Rock Mass	

	Characteristics	130
4.2.3	Study of Rock Exposures in Trans Crete Quarry	134
4.2.3.1	Joint Spacing and Trace Length	134
4.2.3.2	Joint Orientation	135
4.2.3.3	Sketches of Panels	136
4.2.3.4	Summary of Rock Mass	
	Characteristics	140
4.2.4	Study of Rock Exposures in Wax Green Quarry	143
4.2.4.1	Joint Spacing and Trace Length	143
4.2.4.2	Joint Orientation	144
4.2.4.3	Sketches of Panels	145
4.2.4.4	Summary of Rock Mass	
	Characteristics	150
4.2.5	Dominant Spacing and Trace Length	153
4.2.6	Dominant Type of Discontinuity	160
4.2.7	Block Volume, Volumetric Joint Count and Degree of Jointing	162
4.2.8	Dominant Color Chart of Rock Material	164
4.2.9	Boulders Occurrence	165
4.3	Dominant Mass Weathering Profiles	168
4.4	Typical Mass Weathering Profile	172
4.5	Summary	174
<b>5</b>	<b>ROCK MATERIAL PROPERTIES</b>	<b>178</b>
5.1	Introduction	178
5.2	Identification of Weathering Grade	178
5.2.1	Mineralogical Properties	179
5.3	Physical Properties	190
5.3.1	Dry Unit Weight	190
5.3.2	Water Absorption	193
5.3.3	Sonic Wave Velocity	197
5.4	Engineering Properties	200
5.4.1	Schmidt Hammer Value	200
5.4.2	Point Load Index	204

	5.4.2.1	Effect of Moisture on Strength	207
	5.4.3	Indirect Tensile Strength	215
	5.4.4	Uniaxial Compressive Strength	218
	5.4.5	Slake Durability Index	222
	5.5	Summary	225
<b>6</b>		<b>A NEW GEOMECHANICAL MODEL FOR SURFACE EXCAVATION</b>	<b>230</b>
	6.1	Introduction	230
	6.2	Practical Excavation	231
	6.3	Applicability of the General Rock Mass Classifications in Surface Excavation	234
	6.4	Effective Parameters in Geomechanical Model for Surface Excavation	237
	6.5	Geomechanical Model for Surface Excavation	240
	6.6	Prediction of Surface Excavation Rate	243
	6.7	Verification of the Geomechanical Model for Surface Excavation	262
	6.8	Summary	267
<b>7</b>		<b>CONCLUSION AND RECOMMENDATION</b>	<b>269</b>
	7.1	Conclusion	269
	7.2	Recommendation	273
		<b>REFERENCES</b>	<b>274</b>
		Appendices A-B	294-313

## LIST OF TABLES

TABLE NO.	TITLE	PAGE
2.1	Material description of different rock types (Dearman, 1974; and ISRM, 1981)	20
2.2	Schematic classification of igneous rocks (Zhang, 2005)	21
2.3	Classification of sedimentary rocks (Zhang, 2005)	23
2.4	Classification of metamorphic rocks (Zhang, 2005)	24
2.5	Commonly designation of grain size (Tatiya, 2005)	33
2.6	Terminology of trace length based on numerical values (B.S. EN ISO 14689-1, 2003)	40
2.7	Terminology of joint spacing based on numerical values (after B.S. EN ISO 14689-1, 2003; and Attewell, 1993)	40
2.8	Weathering stages and boulders in granite (Durgin, 1977)	43
2.9	Rock properties influencing surface excavation	46
2.10	influencing parameters on excavability in different classifications	52
2.11	The most common rock mass classifications	56
2.12	The relation between RQD and rock mass quality (Deere, 1968)	57
2.13	Rock mass rating system (Bieniawski, 1989)	60
2.14	Rating table of $j_w$ (Cai <i>et al.</i> , 2004)	67
2.15	Rating table of $j_s$ (Cai <i>et al.</i> , 2004)	67
2.16	Rating table of $j_a$ (Cai <i>et al.</i> , 2004)	67
2.17	Evolution of weathering profile during the time	70
3.1	Description of rock mass in each mass weathering grade (ISRM, 2007)	81
3.2	Classification of weathered rock (Anon, 1995)	84
3.3	Gamble's slake durability classification (Goodman, 1989)	93
3.4	Descriptions of different parts of of utilized hydraulic excavators	95
3.5	Operational specifications of utilized hydraulic excavators	95
4.1	Geomorphology versus weathering zones in Segamat Quarry	101
4.2	Geomorphology versus weathering zones in Seri Alam Quarry	102
4.3	Geomorphology versus weathering zones in Trans Crete Quarry	104
4.4	Geomorphology versus weathering zones in Wax Green Quarry	106

4.5	Statistics of joint spacing and trace length in Segamat Quarry	109
4.6	Major joint sets in different weathering zones in Segamat Quarry	111
4.7	Sketches of rock exposure in Segamat Quarry	112
4.8	Summary of rock mass characteristics in Segamat Quarry	121
4.9	Statistics of joint spacing and trace length in Seri Alam Quarry	122
4.10	Major joint sets in different weathering zones in Seri Alam Quarry	124
4.11	Sketches of rock exposure in Seri Alam Quarry	125
4.12	Summary of rock mass characteristics in Seri Alam Quarry	133
4.13	Statistics of joint spacing and trace length in Trans Crete Quarry	134
4.14	Major joint sets in different weathering zones in Trans Crete Quarry	135
4.15	Sketches of rock exposure in Trans Crete Quarry	136
4.16	Summary of rock mass characteristics in Trans Crete Quarry	142
4.17	Statistics of joint spacing and trace length in Wax Green Quarry	143
4.18	Major joint sets in different weathering zones in wax green	144
4.19	Sketches of rock exposure in Wax Green Quarry	146
4.20	Summary of rock mass characteristics in Wax Green Quarry	152
4.21	Statistics of joint spacing in different weathering zones	154
4.22	Statistics of joint trace length in different weathering zones	154
4.23	Percentage of joint types in different weathering zones	161
4.24	Block volume in different weathering zones	162
4.25	Volumetric joint count in different weathering zones	163
4.26	Dominant color chart of rock material in different weathering zones	165
4.27	Physical characteristics of boulder in different weathering zones	167
4.28	Statistical analysis of boulder occurrence	167
4.29	Modified weathering zones based on presence of boulders	168
4.30	Dominant profile type A	169
4.31	Dominant profile type B	170
4.32	Dominant profile type C	171
4.33	Dominant profile type D	171
4.34	Typical mass weathering profile of tropically weathered granite	173
5.1	Major mineral compositions of samples	180
5.2	Photomicrographs of weathering grade I	182
5.3	Photomicrographs of weathering grade II	183
5.4	Photomicrographs of weathering grade III	184
5.5	Photomicrographs of weathering grade IV	185
5.6	Photomicrographs of weathering grade V	186
5.7	Major minerals in each weathering grade	190
5.8	The results of dry unit weight test in Segamat Quarry	191
5.9	The results of dry unit weight test in Seri Alam Quarry	191
5.10	The results of dry unit weight test in Trans Crete Quarry	192
5.11	The results of dry unit weight test in Wax Green Quarry	192

5.12	The results of dry unit weight test for combined data	193
5.13	The results of water absorption test in Segamat Quarry	194
5.14	The results of water absorption test in Seri Alam Quarry	194
5.15	The results of water absorption test in Trans Crete Quarry	195
5.16	The results of water absorption test in Wax Green Quarry	195
5.17	The results of water absorption test for combined data	196
5.18	The results of sonic wave velocity test in Segamat Quarry	198
5.19	The results of sonic wave velocity test in Seri Alam Quarry	198
5.20	The results of sonic wave velocity test in Trans Crete Quarry	198
5.21	The results of sonic wave velocity test in Wax Green Quarry	198
5.22	The results of sonic wave velocity test for combined data	199
5.23	The results of Schmidt hammer value in Segamat Quarry	202
5.24	The results of Schmidt hammer value in Seri Alam Quarry	202
5.25	The results of Schmidt hammer value in Trans Crete Quarry	202
5.26	The results of Schmidt hammer value in Wax Green Quarry	202
5.27	The results of Schmidt hammer value for combined data	204
5.28	The results of point load index in Segamat Quarry	205
5.29	The results of of point load index in Seri Alam Quarry	205
5.30	The results of point load index in Trans Crete Quarry	206
5.31	The results of point load index in Wax Green Quarry	206
5.32	The results of point load index for combined data	207
5.33	Moisture contents versus $I_{s(50)}$ in Segamat Quarry	209
5.34	Moisture contents versus $I_{s(50)}$ in Seri Alam Quarry	210
5.35	Moisture contents versus $I_{s(50)}$ in Trans Crete Quarry	210
5.36	Moisture contents versus $I_{s(50)}$ in Wax Green Quarry	211
5.37	Moisture contents versus $I_{s(50)}$ for combined data	213
5.38	The results of tensile strength test in Segamat Quarry	216
5.39	The results of tensile strength test in Seri Alam Quarry	217
5.40	The results of tensile strength test in Trans Crete Quarry	217
5.41	The results of tensile strength test in Wax Green Quarry	217
5.42	The results of tensile strength test for combined data	218
5.43	The results of uniaxial compressive strength in Segamat Quarry	219
5.44	The results of uniaxial compressive strength in Seri Alam Quarry	220
5.45	The results of uniaxial compressive strength in Trans Crete Quarry	220
5.46	The results of uniaxial compressive strength in Wax Green Quarry	220
5.47	The results of uniaxial compressive strength for combined data	221
5.48	The results of slake durability test in Segamat Quarry	223
5.49	The results of slake durability test in Seri Alam Quarry	223
5.50	The results of slake durability test in Trans Crete Quarry	223
5.51	The results of slake durability test in Wax Green Quarry	223
5.52	The results of slake durability test for combined data	225

6.1	The results of practical excavation in Segamat Quarry	233
6.2	The results of practical excavation in Seri Alam Quarry	233
6.3	The results of practical excavation in Trans Crete Quarry	234
6.4	The results of practical excavation in Wax Green Quarry	234
6.5	Geomechanical parameters in different rock mass classification systems	235
6.6	Summary of the statistical model for dependent Q	239
6.7	Coefficients of predictor parameters for dependent Q	239
6.8	Excluded parameters from the model	240
6.9	Suggested maximum rate for predictor parameters	241
6.10	Proposed chart of Excavation Index of Granite (EIG)	242
6.11	Parameters and their rates based on the EIG chart for completely weathered zones	244
6.12	Parameters and their rates based on the EIG chart for highly weathered zones	247
6.13	Parameters and their rates based on the EIG chart for moderately weathered zones	249
6.14	Parameters and their rates based on the EIG chart for slightly weathered zones	250
6.15	Parameters and their rates based on the EIG chart for fresh zones	253
6.16	EIG values versus Q	255
6.17	Proposed chart of excavability classification in granite	258
6.18	Parameters and their rates based on the EIG chart for excavated zones in Menang Granite Quarry	264
6.19	Predicted results of excavation in Menang Granite Quarry	265
6.20	Description of parts and operational properties of Volvo EC380D	266
6.21	Operational specifications of Volvo EC380D	266
6.22	The results of practical excavation in Menang Granite Quarry	267
6.23	Predicted range of excavation rate versus practical excavation rate	267

## LIST OF FIGURES

FIGURE NO.	TITLE	PAGE
1.1	Location map of the studied sites	7
2.1	Applications of underground excavation (Tatiya, 2005)	10
2.2	Applications of surface excavation (Tatiya, 2005)	11
2.3	Parameters of rock mass related to excavation (Matti, 1999)	12
2.4	The wedge cutter created a tensile breakage in rock (Bilgin, 1977)	14
2.5	Idealized breakage mechanism (Rostami and Ozdemir, 1993)	15
2.6	Surface excavators based on their application (Tatiya, 2005)	16
2.7	Different surface excavators (Tatiya, 2005)	17
2.8	Main parts of the arm of hydraulic excavator (Haddock, 1998)	18
2.9	Swing and its components in hydraulic excavator (Haddock, 1998)	19
2.10	Different types of feet in hydraulic excavators (Haddock, 1998)	19
2.11	The main features constituting a rock mass (Palmstrom, 2000)	25
2.12	The relationship between the strength of rock mass and the sample size (Palmstrom, 2000)	26
2.13	The effect of weathering on (a) clay minerals and (b) residual oxides in igneous rocks (Summerfield, 1991)	29
2.14	Tropical weathering profile in (a) continuously humid climate, and (b) alternating wet and dry climate (Nagle, 2000)	30
2.15	Rock material characteristics (Singh and Goel, 2011)	31
2.16	Trace length of different types of discontinuities (Piteau, 1973)	37
2.17	Main features of a joint (Palmstrom, 1995)	39
2.18	Determination of rock mass homogeneity by sample size (Hoek <i>et al.</i> , 1995)	44
2.19	M-RMR system flowchart (Unal, 1996)	62
2.20	The GSI classification chart (Hoek, 1994)	64
2.21	The modified GSI classification chart (Cai <i>et al.</i> , 1995)	65
2.22	Schematic block consisting of three joint sets (Cai <i>et al.</i> , 2004)	66
2.23	Typical weathering profiles of granitic rock in Peninsular Malaysia (Komoo, 1987, 1985)	73
3.1	Flow chart of research methodology	76



3.2	Geological map of Johor including the location of (a) Segamat Quarry, (b) Seri Alam Quarry, (c) Trans Crete Quarry, (d) Wax Green Quarry and (e) Menanag Granite Quarry (Rajah <i>et al.</i> , 1982)	77
3.3	Overviews of (a) Segamat Quarry, (b) Seri Alam Quarry, (c) Trans Crete Quarry and (d) Wax Green Quarry	79
3.4	Some parameters to characterize the rock mass (after wyllie, 1999)	88
3.5	Types of point load test (Franklin, 1970)	88
3.6	Indirect tensile (Brazilian) test equipment (ISRM, 2007)	90
3.7	Procedure of core preparation from a bulk sample	91
3.8	Standard apparatus of slake durability test (ISRM, 2007)	92
3.9	Mechanical excavators including (a) Hitachi EX300-5, (b) Komatsu PC300-6, (c) Komatsu PC410-5, (d) and Kobelco SK330	94
3.10	Different parts of a typical hydraulic excavator in (a) side view, (b) front view and (c) operational view	94
4.1	Overview of assigned panels in (a) Segamat Quarry, (b) SeriAlam Quarry, (c) Trans Crete Quarry and (d) Wax Green Quarry	99
4.2	Identified weathering zones as (a) fresh, (b) slightly weathered, (c) moderately weathered, (d) highly weathered, (e) completely weathered and (f) residual soil.	100
4.3	Sketch of rock exposure in Segamat Quarry	103
4.4	Sketch of rock exposure in Seri Alam Quarry	103
4.5	Sketch of rock exposure in Trans Crete Quarry	105
4.6	Sketch of rock exposure in Wax Green Quarry	107
4.7	Sample joints in (a) fresh, (b) slightly weathered, (c) moderately weathered, (d) highly weathered and (e) completely weathered and (f) a partially filled joint	108
4.8	Overall frequency of joint spacing in (a) fresh and (b) slightly weathered zones	155
4.9	Overall frequency of joint trace length in (a) fresh, (b) slightly weathered and (c) moderately weathered zones	157
4.10	Overall mean joint spacing in different weathering zones	159
4.11	Overall mean joint trace length in different weathering zones	160
4.12	Overall percentages of joint types in different weathering zones	162
4.13	Volumetric joint count in different weathering zones	163
4.14	Samples of discoloration at joint surfaces	164
4.15	Samples of boulder occurrence in highly and completely weathered zones	166
5.1	The mineral peak list of weathering grade I	187
5.2	The mineral peak list of weathering grade II	187

5.3	The mineral peak list of weathering grade III	188
5.4	The mineral peak list of weathering grade IV	188
5.5	The mineral peak list of weathering grade V	189
5.6	Unit weight test for a rock sample	190
5.7	Dry unit weight versus weathering grades in (a) Segamat Quarry, (b) Seri Alam Quarry, (c) Trans Crete Quarry and (d) Wax Green Quarry	192
5.8	Dry unit weight versus weathering grades for combined data	193
5.9	Water absorption test	194
5.10	Water absorption versus weathering grade in (a) Segamat Quarry, (b) Seri Alam Quarry, (c) Trans Crete Quarry, (d) Wax Green Quarry	195
5.11	Water absorption versus weathering grade for combined data	196
5.12	Sonic wave velocity test on a core specimen	197
5.13	Velocity of primary wave versus weathering grades in (a) Segamat Quarry, (b) Seri Alam Quarry, (c) Trans Crete Quarry and (d) Wax Green Quarry	199
5.14	Velocity of primary wave versus weathering grades for combined data	200
5.15	In-situ application of Schmidt hammer	201
5.16	Schmidt hammer values versus weathering grades in (a) Segamat Quarry, (b) Seri Alam Quarry, (c) Trans Crete Quarry and (d) Wax Green Quarry	203
5.17	Schmidt hammer values versus weathering grades for combined data	204
5.18	Point load test operation	204
5.19	Point load index versus weathering grades in (a) Segamat Quarry, (b) Seri Alam Quarry, (c) Trans Crete Quarry, (d) Wax Green Quarry	206
5.20	Point load index versus weathering grades for combined data	207
5.21	Lump samples soaked in water containers for different immersion times	208
5.22	A crumbled sample of grade V after 60 minutes immersion time	208
5.23	Point load index versus moisture content Segamat Quarry	211
5.24	Point load index versus moisture content in Seri Alam Quarry	212
5.25	Point load index versus moisture content in Trans Crete Quarry	212
5.26	Point load index versus moisture content in Wax Green Quarry	213
5.27	Point load index versus moisture content for combined data	214
5.28	Strength reduction related to increment of moisture content	215
5.29	Indirect tensile strength test	216
5.30	Tensile strength versus weathering grades in (a) Segamat Quarry, (b) Seri Alam Quarry, (c) Trans Crete Quarry and (d) Wax Green Quarry	217

5.31	Tensile strength versus weathering grades for combined data	218
5.32	Uniaxial compressive strength test	219
5.33	Uniaxial compressive strength versus weathering grades in (a) Segamat Quarry, (b) Seri Alam Quarry, (c) Trans Crete Quarry and (d) Wax Green Quarry	220
5.34	Uniaxial compressive strength versus weathering grades for combined data	221
5.35	Slake durability test	222
5.36	Slake durability index versus weathering grades in (a) Segamat Quarry, (b) Seri Alam Quarry, (c) Trans Crete Quarry and (d) Wax Green Quarry	224
5.37	Slake durability index versus weathering grades for combined data	225
6.1	Sequences of sample excavation cycle in $CW_a$	232
6.2	Sequences of sample excavation cycle in $HW_a$	232
6.3	RQD versus Q	235
6.4	$RMR_{basic}$ and RMR versus Q	236
6.5	M-RMR versus Q	236
6.6	GSI and M-GSI versus Q	236
6.7	Proposed graph of mass homogeneity versus RSR	238
6.8	Correlation between Q and the EIG values	257
6.9	Classes of EIG versus Q	258
6.10	Graphical assessment of excavability in (a) Segamat Quarry, (b) Seri Alam Quarry, (c) Trans Crete Quarry and (d) Wax Green Quarry	259
6.11	Overview of Menang Granite Quarry	262
6.12	Excavated zones in Menang Granite Quarry	263
6.13	Volvo EC380D	265
6.14	Parts of Volvo EC380D in (a) side view, (b) front view and (c) operational view	266

## LIST OF ABBREVIATIONS

BS	-	British Standard
GSI	-	Geological Strength Index
ISRM	-	International Society of Rock Mechanics
M-RMR	-	Modified Rock Mass Rating
RMR	-	Rock Mass Rating
RQD	-	Rock Quality Designation
RSR	-	Rock:Soil Ratio
SHV	-	Schmidt Hammer Value
UCS	-	Uniaxial Compressive Strength
XRD	-	X-ray Diffraction

**LIST OF APPENDICES**

<b>APPENDIX</b>	<b>TITLE</b>	<b>PAGE</b>
A	Distribution of joint characteristics in various weathering zones	294
B	Streographic projection plots in various weathering zones	307

## **CHAPTER 1**

### **INTRODUCTION**

#### **1.1 Background**

The planning of an excavation project relies greatly on the knowledge of geological and geotechnical conditions of the site. An appropriate investigation able to provide a picture and assessment, as realistic as possible, of conditions to be encountered. The goal of these investigations is the description and evaluation of the ground conditions as they affect the excavation work. Based on this, a proper design and planning of measures for excavation work can be produced. They should be adapted to the anticipated excavation process to provide specific details and data for designing, tendering and estimating the excavation work and selecting the type of contract and invoicing.

In tropical regions, wet and humid environment impedes and complicates the ground's engineering behavior. One of the issues in these areas is the abundance of weathered rocks that dealing with is a major concern in foundation, slope stability, embankment failure problems and excavation works. Weathering of surface rocks in tropical climates has produced thick weathering profiles that consist a number of sub classifications or weathering states that require adequate judgement of their characteristics for efficient excavation.

A major problem confronting geotechnical engineers in the tropics is how to characterize the local lithologies accurately and predict their in-service performance reliably. It should be pointed out that a realistic geotechnical characterization of

tropically weathered rock mass requires a broad understanding of the engineering geology of the tropical environment, which relates specifically to an appreciation of the significant genetic consequences of the weathering process and its geotechnical implications. The key factors that should be considered in this geological engineering assessment include the geomorphology, groundwater condition, the position, mineralogy and fabric of the rock in the weathering profile.

The available literature has shown scholars' effort to classify systematically the characterization of rock masses with the purpose of evaluating their behavior as accurate as possible. The significance of rock mass classification scheme is also observable in creating a characterization and composition image of any rock mass for estimating the preliminary requirements of feasibility design. However, most of the classifications have shown rigorous application of the classical analytical methods to the design of excavation in tropically weathered rocks is not always successful, generally because of a limited knowledge of the engineering properties and the in-service performance of these lithologies. In addition, prudence dictates that the generalized weathering profiles in the published literature should be adapted for local conditions as appropriate.

In order to characterize weathering profiles, it is desirable to distinguish between residual soils and those zones of weathered rock that are essentially soil-like but retaining the original rock fabric. This is to enable judicious choice between the relevant rock mechanics and soil mechanics parameters to be employed in the design analysis. Most of researchers tried to develop the weathering profile and determine a method to estimate the engineering properties of granitic rock mass based on geological identification, engineering recognition and laboratory testing.

## **1.2 Problem Statement**

There are several issues associated with weathered rocks, which may affect the surface excavation work in tropical region. Weathering profile of rock masses can be variable and unpredictable. They may contain materials of wide range of

strengths together with structures inherited from the parent rock. This issue is called structural complexity or heterogeneity of the rock mass. Heterogeneity of weathered rock mass may cause difficulties for surface excavation works. Major changes in degree of weathering may lead to rapidly changing requirement both for method of excavation and for engineering design. Another specific feature of weathering in tropical region is boulder occurrence as blocks of fresh material within a matrix of severely weathered rock. This phenomena can be problematic in surface excavation design and performance because it can interfere the operation of mechanical excavator and decreased the efficiency of excavation. Although a set of researchers investigated the tropically weathered granitic rock, there are still confusions with behavior of the heterogenous zones that exist between the transition of the rock to soil.

There are some parameters of rock material and rock mass that affect surface excavation of rock mass. There is no single method that can define all the properties of rock, while many tests and site investigations give either a direct or an indirect value of these parameters. Consequently, effective parameters of rock material and rock mass for surface excavation have to be determined to avoid performing redundant, time consuming and costly laboratory tests and site surveys. The importance of rock parameters in each study may differ because of the differences in rock type and weathering process due to different climate conditions.

In tropical regions, weathering and environmental issues such as mineral decomposition, discontinuities characteristics, presence of iron pan and reduction of strength due to moisture content should be considered as unique features in developing a weathering profile. Moreover, climate condition in tropics can significantly decompose and disintegrate rock mass which results in the production of thick weathering profile. Moreover, one of the issues in surface excavation is related to highly and completely weathered rock mass which makes it difficult to determine the best excavation method and to predict the excavation rate. An important consideration in this regards is determining the differences between mass weathering grades in the weathering profile. Although many researchers have studied the changes of geological and engineering properties of different types of weathered



rocks, few if any have focused on a detailed weathering profile of granite in tropical region based on both material and mass properties including special features such as heterogeneity, boulder occurrence and abrupt changes as a result of tropical weathering process.

### **1.3 Objectives of the Study**

Based on what has been discussed, the ultimate aim of this study was to advance and at the same time simplify the currently available rock mass classifications for excavation purposes in weathered rocks. To this end, the following objectives have been set.

- i. To propose a typical mass weathering profile of tropically weathered granite.
- ii. To investigate the effective parameters of rock material and rock mass for surface excavation in tropically weathered granite.
- iii. To propose a geomechanical model for surface excavation in tropically weathered granite.

### **1.4 Research Questions**

In line with the objectives of this research, the following research questions are defined.

- i. What is the typical weathering profile of tropically weathered granite?
- ii. What are the effective parameters of rock material and rock mass for surface excavation in tropically weathered granite?
- iii. What is the possible geomechanical model for surface excavation in tropically weathered granite?

## 1.5 Scope and Limitations of the Study

In this study special attention is provided to classify geological engineering properties of weathered granite in tropical region for surface excavation work. Therefore, this research was carried out in granite quarries at suitable sites where the profiles of weathering exist clearly and assessable. Based on weathering perspective regarding to excavation, interested zones were identified in these sites. This study comprises of field investigations and measurements as well as laboratory tests and data analysis. Consideration of this study emphasizes on problematic zones of the rock mass where highly to completely weathered rock is located.

The field work was carried out at four granite quarries namely Segamat Quarry, Seri Alam Quarry, Transcrete Quarry and Wax Green Quarry in Johor Bahru, Johor. In addition, another quarry namely Menang Granite Quarry was studied for verification of the applicability of the proposed model. These quarries were chosen because they provide a good exposure of weathering profile and active excavation works are available for this research. These particular areas are underlain by granite, which is of Late Cretaceous to early Tertiary age.

Taking into account the objectives of the research, the facilities available in the studied area and the excavation equipment in the quarries, the present study was carried out within the following limitations.

- i. The location of the study was limited to five granitic quarries in South Malaysia.
- ii. The studied excavation method was limited to surface excavation with direct mechanical excavation without the aid of any drilling or blasting operations.
- iii. The utilized hydraulic excavators were selected upon their availability in the quarries.

## 1.6 Significance of the Study

The prime importance in rock mass description and characterization for any engineering design is to find out the relevant significant parameters. To contribute to the feasibility study of surface excavation, rock mass and material characterization are important to be correlated to mass weathering grades. The important contribution of this study to the body of knowledge was providing comprehensive understanding of mass and material properties of weathered granite in tropical region, providing a typical mass weathering profile of granite and developing a geomechanical model for surface excavation in granite. Ultimately, the mentioned profile and model led to simplified characterization of the complex behavior of weathered granite in tropical region. It is hoped that this work would lead to systematic study of weathered rock mass with the aim of surface excavation.

## 1.7 Study Area

The research was carried out based on the study at the five active quarries located in Johor, Malaysia as listed below. The locations of the sites are shown in Figure 1.1.

- A. Segamat Quarry ( $1^{\circ} 36' 15.19''$  N,  $103^{\circ} 46' 40.63''$  E) located in Ulu Tiram, Johor, Malaysia for initial data collection.
- B. Seri Alam Quarry ( $1^{\circ} 30' 58.66''$  N,  $103^{\circ} 51' 21.94''$  E) located in Masai, Johor, Malaysia for initial data collection.
- C. Trans Crete Quarry ( $1^{\circ} 31' 21.63''$  N,  $103^{\circ} 52' 60.00''$  E) located in Masai, Johor, Malaysia for initial data collection.
- D. Wax Green Quarry ( $1^{\circ} 31' 17.17''$  N,  $103^{\circ} 55' 12.13''$  E) located in Masai, Johor, Malaysia for initial data collection.
- E. Menang Granite Quarry ( $1^{\circ} 41' 51.32''$  N,  $103^{\circ} 29' 46.29''$  E) located in Kulai, Johor, Malaysia for verification of the study.



Figure 1.1 Location map of the studied sites

## REFERENCES

- Alade, S. M. and Olayinka, H. J. (2012). Investigations into Aesthetic Properties of Selected Granites in South Western Nigeria as Dimension Stones. *Journal of Engineering Science and Technology*. 7(4), 418-427.
- American Standards for Testing and Materials (ASTM) (2012). *ASTM D409/D409M*. Standard Test Method for Grindability of Coal by the Hardgrove-Machine Method. West Conshohocken: ASTM International.
- Andrade, P. S. and Saraiva, A. A. (2008). Estimating the Joint Roughness Coefficient of Discontinuities Found in Metamorphic Rocks. *Bulletin of Engineering Geology and the Environment*. 67(3), 425-434.
- Anon (1977). The Description of Rock Masses for Engineering Purposes. Geological Society Engineering Group Working Party Report. *Quarterly Journal of Engineering Geology and Hydrogeology*. 10 (4), 355-388.
- Anon (1995). The Description and Classification of Weathered Rocks for Engineering Purposes. Geological Society Engineering Group Working Party Report. *Quarterly Journal of Engineering Geology and Hydrogeology*. 28 (3), 207-242.
- Arel, E. and Onalp, A. (2004). Diagnosis of the Transition from Rock to Soil in a Granodiorite. *Journal of Geotechnical and Geoenvironmental Engineering*. 130(9), 968-974.
- Arikan, F. and Aydin, N. (2012). Influence of Weathering on the Engineering Properties of Dacites in Northeastern Turkey. *ISRN Soil Science*. 2012, 15.
- Arikan, F., Ulusay, R. and Aydin, N. (2007). Characterization of Weathered Acidic Volcanic Rocks and a Weathering Classification Based on a Rating System. *Bulletin of Engineering Geology and the Environment*. 66(4), 415-430.
- Attewell, P. B., 1993. The Role Engineering Geology in the Design of Surface and Underground Structures. In Hudson, J. A. (Ed.). *Comprehensive Rock Engineering*. Pergamon Press.

- Au, S. W. C. (1996). The Influence of Joint-planes on the Mass Strength of Hong Kong Saprolitic Soils. *Quarterly Journal of Engineering Geology and Hydrogeology*. 29(3), 199-204.
- Aydin, A. (2006). Stability of Saprolitic Slopes: Nature and Role of Field Scale Heterogeneities. *Natural Hazards & Earth System Sciences*. 6(1).
- Azman Kassim and Edy Tonnizam Mohammad (2007). *Laboratory Study of Weathered Rock for Surface Excavation Works*. University Technology Malaysia, Skudai.
- Barton, C. M. (1978). Analysis of Joint Traces. In *19<sup>th</sup> US Symposium on Rock Mechanics (USRMS)*. 1-3 May. Reno, Nevada, 38-42.
- Barton, N., Lien, R. and Lunde, J. (1974). Engineering Classification of Rock Masses for the Design of Rock Support. *Rock Mechanics*. 6(4), 189-236.
- Basarir, H. and Karpuz, C. (2004). A Rippability Classification System for Marls in Lignite Mines. *Engineering Geology*. 74(3-4), 303-318.
- Bell, F. G. (2004) *Engineering Geology and Construction*. Taylor & Francis.
- Bell, F. G. (2007). *Engineering Geology*. (2<sup>nd</sup> ed.). Butterwoth.
- Berner, E. K. and Berner R. A. (1996). *Global Environment: Water, Air and Geochemical Cycles*. Upper Saddle River, N.J.: Prentice Hall.
- Bieniawski, Z. T. (1973). Engineering Classification of Jointed Rock Masses. *South African Institution of Civil Engineers*. 15(12), 335-344.
- Bieniawski, Z. T. (1984). The Design Process in Rock Engineering. *Rock Mechanics and Rock Engineering*. 17(3), 183-190.
- Bieniawski, Z. T. (1989). *Engineering Rock Mass Classifications*. New York: John Wiley & Sons.
- Bilgin, N. (1977). *Investigation into Mechanical Cutting Characteristics of Some Medium and High Strength Rocks*. PhD Thesis. University of Newcastle, UK.
- Bilgin, N., Copur, H. and Balci, C. (2013). *Mechanical Excavation in Mining and Civil Industries*. CRC Press.
- Bland, W. and Rolls, D. (1998). *Weathering : An Introduction to the Scientific Principles*. London: Arnold.
- Blindheim, O. T. (1979). *Full Face Boring of Tunnels*. University of Trondheim. Report 1-79. Trondheim.
- Bray, J. W. (1967). Study of Jointed and Fractured Rock. *Journal of International Society of Rock Mechanics*. 5(2-3), 117-136.

- Braybrooke, J. C. (1988). The State of the Art of Rock Cuttability and Rippability Prediction. *Proceeding 5<sup>th</sup> ANZ Geomechanics Conference*. August. Sydney, 13-42.
- Bridges, M. C. (1975). Presentation of Fracture Data for Rock Mechanics. *Proceedings of the 2<sup>nd</sup> Australia–New Zealand Conference on Geomechanics*. Brisbane, 144-148.
- Brignoli, M. G., Santarelli, F. J. G. and Papamichos, E. G. (1995). Capillary Effects in Sedimentary Rocks: Application to Reservoir Water-flooding. In *the 35<sup>th</sup> US Symposium on Rock Mechanics (USRMS)*. 5-7 June. Reno, Nevada, 619-625.
- British Standards Institution (2003). *B.S. EN ISO 14689-1*. Geotechnical Investigation and Testing, Identification and Classification of Rock. Identification and Description. London: British Standards Institution.
- Broch, E. (1979). Changes in Rock Strength Caused by Water. In *4<sup>th</sup> ISRM Congress*. 2-8 September. Montreux, Switzerland, 71-75.
- Broch, E. and Franklin, J. A. (1972). The Point Load Strength Test. *International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts*. 9(6), 669-697.
- Buss, H. L., Sak, P. B., White, A. F. and Brantley, S. L. (2004). Mineral Dissolution at the Granite–Saprolite Interface. *Proceeding 11<sup>th</sup> International Symposium on Water–Rock Interaction*. 819-823.
- Buss, H. L., Sak, P. B., Webb, S. M. and Brantley, S. L. (2008). Weathering of the Rio Blanco Quartz Diorite, Luquillo Mountains, Puerto Rico: Coupling Oxidation, Dissolution and Fracturing. *Geochimica et Cosmochimica Acta*. 72(18), 4488-4507.
- Cai, M., Kaiser, P. K., Uno, H., Tasaka, Y. and Minami, M. (2004). Estimation of Rock Mass Deformation Modulus and Strength of Jointed Hard Rock Masses Using the GSI System. *International Journal of Rock Mechanics and Mining Sciences*. 41(1), 3-19.
- Call, R. D., Savely, J. P. and Nicholas, D. E. (1976). Estimation of Joint Set Characteristics From Surface Mapping Data. *Proceeding 17<sup>th</sup> US Symposium on Rock Mechanics*. Arizona, 2B2-1–2B2-9.
- Cefrey, H. (2003). *Sedimentary Rocks*. New York: The Rosen Publishing Group.

- Ceryan, S. (2012). Weathering Indices for Assessment of Weathering Effect and Classification of Weathered Rocks: A Case Study From NE Turkey. *Earth Sciences*. 19-44.
- Ceryan, S., Tudes, S. and Ceryan, N. (2008). A New Quantitative Weathering Classification for Igneous Rocks. *Environmental Geology*. 55(6), 1319-1336.
- Chacon, M. A. (1999). *Architectural Stone: Fabrication, Installation and Selection*. John Wiley & Sons.
- Chavez, R. Moser, P. and Schleifer, J. (2000). An Integrated Control System for Blasting and Production Chain Optimisation in Open-pit Mining and Quarrying. In Holmberg, R. (Ed.) *Explosives and Blasting Technique*. (pp. 423-429). Taylor & Francis.
- Chen, Z. (1995). Recent Developments in Slope Stability Analysis. *Proceedings of the 8<sup>th</sup> ISRM Congress*. Tokyo, 1041-1048.
- Coates, D. F. (1964). Classification of Rocks for Rock Mechanics. *International Journal of Rock Mechanics and Mining Science Abstracts*. 1(3), 421-429.
- Copur, H., Bilgin, N., Tuncdemir, H. and Balci, C. (2003). A Set of Indices Based On Indentation Tests for Assessment of Rock Cutting Performance and Rock Properties. *Journal of South African Institute of Mining and Metallurgy*. 103(9), 589–600.
- Dearman, W. R. (1974). Weathering Classification in the Characterisation of Rock for Engineering Purposes in British Practice. *Bulletin of the International Association of Engineering Geology*. 9(1), 33-42.
- Dearman, W. R. (1976). Weathering Classification in the Characterisation of Rock: A Revision. *Bulletin of the International Association of Engineering Geology - Bulletin de l'Association Internationale de Géologie de l'Ingénieur*. 14(1), 123-127.
- Dearman, W. R. (1995). Description and Classification of Weathered Rocks for Engineering Purposes: the Background to the BS5930:1981 Proposals. *Quarterly Journal of Engineering Geology and Hydrogeology*. 28(3), 267-276.
- Dearman, W. R., Baynes, F. J. and Irfan, T. Y. (1978). Engineering Grading of Weathered Granite. *Engineering Geology*. 12(0), 345-374.
- Deere, D. U. (1964). Technical Description of Rock Cores for Engineering Purposes. *Felsmechanik und Ingenieurgeologie*. 1(1), 16-22.



- Deere, D. U. (1968). Geological Considerations. In Stagg, R. G. and Zienkiewicz, D. C. (Eds.) *Rock Mechanics in Engineering Practice*. (pp. 1-20). Division of Civil Engineering, School of Engineering, University of Wales, Swansea, New York: John Wiley & Sons.
- Deere, D. U., Hendron, A. J., Patton, F. D. and Cording, E.J. (1967). Design of Surface and Near Surface Construction in Rock. *The 8<sup>th</sup> U.S. Symposium on Rock Mechanics (USRMS)*. 15-17 September. Minneapolis, Minnesota, 237-302.
- Deere, D.U. and Miller, R. D. (1966). *Engineering Classification and Index Properties for Intact Rock*. Technical Report No. AFWL-TR-65-116. University of Illinois.
- Deere, D. U., Peck, R. B., Monsees, J. E. and Schmidt, B. (1969). Design of Tunnel Liners and Support System. *Office of High Speed Ground Transportation, U.S. Department of Transportation*. Contract No. 3-0152.
- Deketh, H. J. R., Grima, M. A., Hergarden, I. M., Giezen, M. and Verhoef, P. N. W. (1998). Towards the Prediction of Rock Excavation Machine Performance. *Bulletin of Engineering Geology and the Environment*. 57(1), 3-15.
- Dey, K. and Ghosh, A. K. (2008). Predicting "Cuttability" with Surface Miners - A Rock Mass Classification Approach. *Journal of Mines, Metals and Fuels*. 56(5-6), 85-91.
- Dey, K. and Ghose, A. K. (2011). Review of Cuttability Indices and A New Rockmass Classification Approach for Selection of Surface Miners. *Rock Mechanics and Rock Engineering*. 44(5), 601-611.
- Dobereiner, L., Durville, J. L. and Restitutito, J. (1993). Weathering of the Massiac Gneiss (Massif Central, France). *Bulletin of the International Association of Engineering Geology - Bulletin de l'Association Internationale de Géologie de l'Ingénieur*. 47(1), 79-96.
- Doyuran, V., Ayday, C. and Karahanoglu, N. (1993). Statistical Analyses of Discontinuity Parameters of Gölbaşı (Ankara) Andesites, Süpren (Eskişehir) Marble and Porsuk Dam (Eskişehir) Peridotite in Turkey. *Bulletin of the International Association of Engineering Geology-Bulletin de l'Association Internationale de Géologie de l'Ingénieur*. 48(1), 15-31.

- Durgin, P. B. (1977). Landslides and the Weathering of Granitic Rocks. In Coates, D. R. (Ed.). *Landslides*. (pp.127-131). Colorado: The Geological Society of America.
- Duzgoren-Aydin, N. S. and Aydin, A. (2003). Chemical Heterogeneities of Weathered Igneous Profiles: Implications for Chemical Indices. *Environmental & Engineering Geoscience*. 9(4), 363-376.
- Edelbro, C. (2004). *Evaluation of Rock Mass Strength Criteria*. Licentiate Thesis. Luleå University of Technology.
- Edy Tonnizam Mohamad, Khairul Anuar Kassim and Komoo, I. (2005). To Rip or To Blast : An Overview of Existing Excavation Assessment. *International Conference on Engineering and Technology (BICET 2005)*. Brunei, 27-36.
- Ehlen, J. (2002). Some Effects of Weathering on Joints in Granitic Rocks. *Catena*. 49(1-2), 91-109.
- Einstein, H. H. and Baecher, G. B. (1982). Probabilistic and Statistical Methods in Engineering Geology I. Problem Statement and Introduction to Solution. In L. Müller (Ed.). *Ingenieurgeologie und Geomechanik als Grundlagen des Felsbaues / Engineering Geology and Geomechanics as Fundamentals of Rock Engineering*. (pp. 47-61). Springer.
- Eissa, E. A. and Sen, Z. (1991). Technical Note: Intact Length Correction in Relation to Rock Quality Designation. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*. 411-419.
- Evans, I. (1962). A Theory of the Basic Mechanics of Coal Ploughing. *Proceedings of the International Symposium on Mining Research*. February. University of Missouri, Pergamon Press, 761-768.
- Evans, I. and Pomeroy, C. D. (1966). *Strength Fracture and Workability of Coal*. Oxford; New York: Pergamon Press.
- Fahimifar, A. and Soroush, H. (2007). A Moisture Index Classification System for Rocks (MiC System). *Rock Mechanics and Rock Engineering*. 40(1), 63-79.
- Fletcher, R. C., Buss, H. L. and Brantley, S. L. (2006). A Spheroidal Weathering Model Coupling Porewater Chemistry to Soil Thicknesses During Steady-state Denudation. *Earth and Planetary Science Letters*. 244(1), 444-457.
- Fookes, P. G., Dearman, W. R. and Franklin, J. A. (1971). Some Engineering Aspects of Rock Weathering with Field Examples From Dartmoor and

- Elsewhere. *Quarterly Journal of Engineering Geology and Hydrogeology*. 4(3), 139-185.
- Fowell, R. J. and Johnson, S. T. (1982). Rock Classification and Assessment for Rapid Excavation. In Farmer, I.W. (Ed.) *Proceeding of Symposium. Strata Mechanics*. (pp. 241-244). New York: Elsevier.
- Fowell, R. J. and Johnson, S. T. (1991). Cuttability Assessment Applied to Drag Tool Tunneling Machines. *Proceeding 7<sup>th</sup> International Congress Rock Mechanics*. Aachen, 985-990.
- Franklin, J. A. (1970). Observations and Tests for Engineering Description and Mapping of Rocks. *Proceeding 2<sup>nd</sup> International Congress ISRM*. September. Belgrade, 11-16.
- Franklin, J. A., Broch, E. and Walton, G. (1971). Logging the Mechanical Character of Rock. *Transactions of the Institution of Mining and Metallurgy, Section A*. 80, 1-9.
- Franklin, J. A. and Chandra, R., (1972). The Slake-durability Test. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*. 9(3), 325-328.
- Franklin, J. A. and Dusseault, M. B. (1989). *Rock Engineering*. New York: McGraw-Hill.
- Gamble, J. C. (1971). *Durability—Plasticity classification of shales and other argillaceous rocks*. Ph.D Thesis, University of Illinois.
- Gehring, K. H. (1980). Abb.4a. The Voest Alpine Rock Cuttability Index.
- Gehring, K. H. (1992). Evaluation of Cutting Performance for VASM, Internal Report BBV.
- Goel, R. K., Jethwa, J. L. and Paithankar, A. G. (1996). Correlation Between Barton's Q and Bieniawski's RMR—A New Approach. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*. 33(2), 179-181.
- Gokceoglu, C., Ulusay, R. and Sonmez, H. (2000). Factors Affecting the Durability of Selected Weak and Clay Bearing Rocks from Turkey, with Particular Emphasis on the Influence of the Number of Drying and Wetting Cycles. *Engineering Geology*. 57(1), 215-237.
- Gokceoglu, C., Zorlu, K., Ceryan, S. and Nefeslioglu, H. A. (2009). A Comparative Study on Indirect Determination of Degree of Weathering of Granites From

- Some Physical and Strength Parameters by Two Soft Computing Techniques. *Materials Characterization*. 60(11), 1317-1327.
- Goodman, R. E. (1989). *Introduction to Rock Mechanics*. New York: John Wiley & Son.
- Gumede H. and Stacey, T. R. (2007). Measurement of Typical Joint Characteristics in South African Gold Mines and the Use of These Characteristics in the Prediction of Rock Falls. *The Journal of The Southern African Institute of Mining and Metallurgy*. 107, 335-344.
- Gupta, A. S. and Rao, S. K. (2001). Weathering Indices and Their Applicability for Crystalline Rocks. *Bulletin of Engineering Geology and the Environment*. 60(3), 201-221.
- Hack, H. R. G. K. (1996). *Slope Stability Probability Classification - SSPC*. Technische Universiteit Delft, The Netherlands.
- Hack, R., Price, D. and Rengers, N. (2003). A New Approach to Rock Slope Stability—A Probability Classification (SSPC). *Bulletin of Engineering Geology and the Environment*. 62(2), 167-184.
- Haddock, K. (1998) *Giant Earthmovers*. USA: MBI.
- Hadjigeorgiou, J. and Poulin, R. (1998). Assessment of Ease of Excavation of Surface Mines. *Journal of Terramechanics*. 35(3), 137-153.
- Hall, K., Arocena, J. M., Boelhouwers, J. and Liping, Z. (2005). The Influence of Aspect on the Biological Weathering of Granites: Observations From the Kunlun Mountains, China. *Geomorphology*. 67(1–2), 171-188.
- Hassani, F. P., Scoble, M. J. and Whittaker, B. N. (1980). Application of Point Load Test to Strength Determination of Rock Proposals for a New Size Correction Chart. *Proceeding 21<sup>st</sup> U.S symposium Rock Mechanics*. 27-30 May. Rolla, Missouri, 543-565.
- Heidari, M., Momeni, A. A. and Naseri, F. (2013). New Weathering Classifications for Granitic Rocks Based on Geomechanical Parameters. *Engineering Geology*. 166, 65-73.
- Heidari, M., Khanlari, G. R., Momeni, A. A. and Jafargholizadeh, H. (2011). The Relationship Between Geomechanical Properties and Weathering Indices of Granitic Rocks, Hamedan, Iran. *Geomechanics and Geoengineering: An International Journal*. 6(1), 59-68.

- Hencher, S. R. and McNicholl, D. P. (1995). Engineering in Weathered Rock. *Quarterly Journal of Engineering Geology and Hydrogeology*, 28(3), 253-266.
- Hoek, E. (1994). Strength of Rock and Rock Masses. *ISRM News Journal*. 2(2), 4-16.
- Hoek, E. and Bray, J. W. (1981). *Rock Slope Engineering*. (3<sup>th</sup> ed.). London: The Institution of Mining and Metallurgy.
- Hoek, E. and Brown, E. T. (1980). *Underground Excavations in Rock*. London: Institution of Mining and Metallurgy.
- Hoek, E., Kaiser, P. K. and Bawden, W. F. (1995). *Support of Underground Excavations in Hard Rock*. CRC Press.
- Hoek, E. and Marinos, P. (2000). Predicting Tunnel Squeezing Problems in Weak Heterogeneous Rock Masses. *Tunnels and Tunnelling International*. 32(11), 45-51.
- Hoek, E., Marinos, P. G. and Marinos, V. P. (2005). Characterisation and Engineering Properties of Tectonically Undisturbed but Lithologically Varied Sedimentary Rock Masses. *International Journal of Rock Mechanics and Mining Sciences*. 42(2), 277-285.
- Hoek, E. and Marinos, P. G. (2009). Tunnelling in Overstressed Rock. *Paper Presented at the EUROCK2009*. 29-31 October. Dubrovnik, Croatia, 29-31.
- Howarth, D. F. and Rowlands, J. C. (1987). Quantitative Assessment of Rock Texture and Correlation with Drillability and Strength Properties. *Rock Mechanics and Rock Engineering*. 20(1), 57-85.
- Hume, C. D. (2011). *Numerical Validation and Refinement of Empirical Rock Mass Modulus Estimation*. MSc Thesis. Queen's University, Kingston, Ontario, Canada.
- Inyang, H. I. (1991). Development of a Preliminary Rock Mass Classification Scheme for Near-Surface Excavation. *International Journal of Surface Mining, Reclamation and Environment*. 5(2), 65-73.
- Irfan, T. Y. (1996). Mineralogy, Fabric Properties and Classification of Weathered Granites in Hong Kong. *Quarterly Journal of Engineering Geology and Hydrogeology*. 29(1), 5-35.

- Irfan, T. Y. (1999). Characterization of Weathered Volcanic Rocks in Hong Kong. *Quarterly Journal of Engineering Geology and Hydrogeology*. 32(4), 317-348.
- Irfan, T. Y. and Powell, G. E. (1985). Engineering Geological Investigations for Pile Foundations on a Deeply Weathered Granitic Rock in Hong Kong. *Bulletin of the International Association of Engineering Geology - Bulletin de l'Association Internationale de Géologie de l'Ingénieur*. 32(1), 67-80.
- International Society of Rock Mechanics (ISRM) (1981). Basic Geotechnical Description of Rock Masses. *International Journal of Rock Mechanics Mining Sciences and Geomechanics Abstracts*. 18, 85-110.
- International Society of Rock Mechanics (ISRM) (1985). Commission on Testing Methods. Suggested Method for Determining Point Load Strength. *International Journal of Rock Mechanics, Mineral Sciences and Geomechanics*. Abstract 22, 51-60.
- International Society of Rock Mechanics (ISRM) (2007). *The Complete ISRM Suggested Methods for Rock Characterization, Testing and Monitoring [1974-2006]*. In Ulsay, R., Hudson, J. (Eds.). International Society of Rock Mechanics.
- Jerram, D. and Petford, N. (2011). *The Field Description of Igneous Rocks*. (2<sup>nd</sup> ed.). West Sussex, U.K: John Wiley & Sons.
- Jimeno, E. L. and Carcedo, F. J. A. (1995). *Drilling and Blasting of Rocks*. Taylor & Francis.
- JKR (1998). Minit Mesyuarat Definition Rock, Unsuitable Material & Concrete Road Kerb, Mac, Kuala Lumpur.
- Karpuz, C. (1990). A classification System for Excavation of Surface Coal Measures. *Mining Science and Technology*. 11(2), 157-163.
- Karpuz, C. and Pasamehmetoglu, A. G. (1997). Field Characterisation of Weathered Ankara Andesites. *Engineering Geology*. 46(1), 1-17.
- Khanlari, G. R., Heidari, M. and Momeni, A. A. (2012). Assessment of Weathering Processes Effect on Engineering Properties of Alvand Granitic Rocks (West of Iran), Based on Weathering Indices. *Environmental Earth Sciences*. 67(3), 713-725.
- Kirsten, H. A. D., (1982). A Classification System for Excavation in Natural Materials. *The Civil Engineer in South Africa*. 24(7), 293-308.

- Komoo, I. (1985). Engineering Properties of Weathered Rock Profiles in Peninsular Malaysia. *Proceedings of the 8<sup>th</sup> Southeast Asian Geotechnical Conference*. March 11-15. Kuala Lumpur, Malaysia, 3–81 – 3–86.
- Komoo, I. (1987). Engineering Properties of the Igneous Rocks in Peninsular Malaysia. *Proceeding 6<sup>th</sup> Regional Conference on Geology, Mineral and Hydrocarbon Resources of Southeast Asia*. 6-12 July. Jakarta, Indonesia, 445-458.
- Komoo, I. (1995a). Weathering as an Important Factor in Assessing Engineering Properties of Rock Material. *Forum on Soil and Rock Properties. Geological Society of Malaysia*. Universiti Malaya, Kuala Lumpur. 31-35.
- Komoo, I. (1995b). Syarahan Perdana Geologi Kejuruteraan Perspektif Rantau Tropika Lembap. Universiti Kebangsaan Malaysia.
- Komoo, I. (1998). Deep Weathering: Major Cause of Slope Failure in Wet Tropical Terrain. *Proceedings of 8<sup>th</sup> International Congress. International Association for Engineering Geology and the Environment*. 21-25 September. Vancouver, Canada, 1773-1778.
- Komoo, I., Kadderi Md.Desa, Hamzah Mohammad, Abdul Ghani Rafek and Tan Boon Kong, (1991). Systematic Approach in The Characterisation of Granitic Weathering Profiles in Tropical Terrain. *Warta Geologi*. 17 (3), 105-109.
- Komoo, I. and Mogana, S. N. (1988). Physical Characterization of Weathering Profiles of Clastic Metasediments in Peninsular Malaysia. *Proceeding 2<sup>nd</sup> Conference on Geomechanic in Tropical Soils*. Singapore, 37-42.
- Komoo, I. and Yaakub, J. (1990). Engineering Properties of Weathered Metamorphic Rocks in Peninsular Malaysia. In *6<sup>th</sup> International IAEG Congress. AA Balkema, Rotterdam*, 665-672.
- Koo, Y. C. (1982). Relict Joints in Completely Decomposed Volcanics in Hong Kong. *Canadian Geotechnical Journal*. 19(2), 117-123.
- Kramadibrata, S. (1996). *The Influence of Rock Mass and Intact Rock Properties on the Design of Surface Mines with Particular Reference to the Excavatability of Rock*. PhD Thesis, Curtin University of Technology School of Civil Engineering.
- Kulatilake, P. H. S. W., Chen, J., Teng, J., Pan, G., Shufang, X. (1996). Discontinuity Geometry Characterization in A Tunnel Close to The Proposed Permanent Shiplock Area of The Three Gorges Dam Site in China.

*International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*. 33(3):255–277.

- Kulatilake, P. H. S. W., Um, J., Wang, M., Escandon, R. F. and Narvaiz, J. (2003). Stochastic Fracture Geometry Modeling in 3-D Including Validations for A Part of Arrowhead East Tunnel, California, USA. *Engineering geology*. 70(1), 131-155.
- Lan, H. X., Hu, R. L., Yue, Z. Q., Lee, C. F. and Wang, S. J. (2003). Engineering and Geological Characteristics of Granite Weathering Profiles in South China. *Journal of Asian Earth Sciences*, 21(4), 353-364.
- Laubscher, D. H. (1975). Class Distinction in Rock Masses. *Coal, Gold and Base Minerals of South Africa*. 23.
- Laubscher, D. H. (1990). A Geomechanics Classification System for the Rating of Rock Mass in Mine Design. *Journal of the Southern African Institute of Mining and Metallurgy*. 90(10), 257-273.
- Laubscher, D. H. (1993). Planning Mass Mining Operations. In Hudson, J. (Ed.) *Comprehensive Rock Engineering*. (pp. 547583). Pergamon Press.
- Laubscher, D. H., Jakubec, J. (2001). The MRMR Rock Mass Classification for Jointed Rock Masses. In Hustrulid, W. A., Bullock R. L. (Eds.) *Underground Mining Methods: Engineering Fundamentals and International Case Studies*. (pp. 475-481). Littleton: Society for Mining, Metallurgy and Exploration.
- Laubscher D. H. and Taylor, H. W. (1976). The Importance of Geomechanics of Jointed Rock Masses in Mining Operations. *Proceedings of the Symposium on Exploration for Rock Engineering*. Cape Town, South Africa, 119-128.
- Lauffer, H. (1958). Classification for Tunnel Construction. *Geologie und Bauwesen*. 24(1), 46-51.
- Lee, S. G. and de Freitas, M. H. (1989). A Revision of the Description and Classification of Weathered Granite and its Application to Granites in Korea. *Quarterly Journal of Engineering Geology and Hydrogeology*. 22(1), 31-48.
- Little, A. L. (1967). The Use of Tropically Weathered Soils in the Construction of Earth Dams. *3<sup>rd</sup> Asian Regional Conference on Soil Mechanics and Foundations Engineering*. Haifa, 35-41.
- Little, A. L. (1969). The Engineering Classification of Residual Tropical Soils. *Proceeding of 7<sup>th</sup> International Conference on Soil Mechanics and Foundation Engineering*. January. Mexico City, 1-10.



- Marinos, P. G. and Hoek, E. (2000). GSI – A Geologically Friendly Tool for Rock Mass Strength Estimation. *Proceeding GeoEng2000 Conference*. November. Melbourne, 1422-1442.
- Marinos, V. P., Marinos, P. G. and Hoek, E. (2005). The Geological Strength Index: Applications and Limitations. *Bulletin of Engineering Geology and the Environment*. 64(1), 55-65.
- Mattern, J. (2006). *Metamorphic Rocks and the Rock Cycle*. New York: The Rosen Publishing Group.
- Matti, H. (1999). *Rock Excavation Handbook*. Sandvik Tamrock Corp.
- Matula, M. and Holzer, R. (1978). Engineering Topology of Rock Masses. *Proceeding of Felsmekanik Kolloquium, Grundlagen und Anwendung der Felsmekanik*. Karlsruhe. Germany, 107-121.
- McFeat-Smith, I. (1977). Rock Property Testing for the Assessment of Tunneling Machine Performance. *Tunnels and Tunneling*. 29-33.
- McLean, A. C. and Gribble, C. D. (2005). *Geology for civil engineers*. (2<sup>nd</sup> ed.) Taylor & Francis.
- Meyer, T. and Einstein, H. H. (2002). Geologic Stochastic Modeling and Connectivity Assessment of Fracture Systems in the Boston Area. *Rock Mechanics and Rock Engineering*. 35(1), 23-44.
- Minty, E. J. and Kearns, G. K. (1983). Rock Mass Workability. In Knight, M. J., Minty, E. J. and Smith, R. B. (Eds.) *Collected Case Studies in Engineering Geology, Hydrogeology and Environmental Geology*. (pp. 59-81). Geological Society of Australia.
- Mishnaevsky, L. L. (1995). Physical Mechanisms of Hard Rock Fragmentation under Mechanical Loading: A Review. *International Journal of Rock Mechanics and Mining Sciences*, 32:763–766.
- Moye, D. G. (1955). Engineering Geology of Snowy Mountains Scheme. *Journal of the Institution of Engineers, Australia*. 27(10-11), 287-298.
- Munsell, (2009). Geological Rock-Color Chart. *Geological Society of America*.
- Murphy, W. L. (1985). Geotechnical Descriptions of Rock and Rock Masses. *US Army Engineer Waterways Experiment Station*. Vicksburg, MS GL-85-3.
- Mohd For Mohd. Amin and Edy Tonnizam Mohamad (2003), Excavatability of Hard Materials in ILP, Mersing: Johor Bahru. Internal Report Universiti Teknologi Malaysia, Unpublished.

- Nagle, G. (2000). *Advanced Geography*. Oxford University Press.
- Nicholson, D. T. and Hencher, S. (1997). Assessing the Potential for Deterioration of Engineered Rock Slopes. *Proceedings of the IAEG symposium*. Athens, 911-917.
- Odling, N. E., Gillespie, P., Bourguine, B., Castaing, C., Chiles, J. P., Chrisensen, N. P., Fillion, E., Genter, A., Olsen, C., Thrance, L., Trice, R., Aarseth, E., Walsh, J. J., Watterson, J. (1999). Variations in Fracture System Geometry and Their Implications for Fluid Flow in Fractured Hydrocarbon Reservoirs. *Petroleum Geoscience*. 5(4), 373-384.
- Ozdemir, L. (1995). Mechanical Mining Technologies. Short Course Notebook. Colorado School of Mines, Mining Engineering. Department, Golden, Colorado.
- Ozdemir, L. (1997). Mechanical Mining. Short Course. Colorado School of Mines, Golden, Colorado.
- Palmstrom, A. (1974). Characterization of Jointing Density and the Quality of Rock Masses (in Norwegian). Internal report, A.B. Berdal, Norway, 26 p.
- Palmstrom, A. (1982). The Volumetric Joint Count - A Useful and Simple Measure of the Degree of Jointing. *Proceeding 4<sup>th</sup> Congress International Association of Engineering Geology*. New Delhi, V.221-V.228.
- Palmstrom, A. (1995). *RMi - A Rock Mass Characterization System for Rock Engineering Purposes*. Ph.D. Thesis, University of Oslo, Norway.
- Palmstrom, A. (2000). Recent Developments in Rock Support Estimates by the RMi. *Journal of Rock Mechanics and Tunnelling Technology*. 6(1), 1-19.
- Palmstrom, A. (2005). Measurements of and Correlations Between Block Size and Rock Quality Designation (RQD). *Tunnelling and Underground Space Technology*. 20(4), 362-377.
- Palmstrom, A. (2009). Combining the RMR, Q and RMi Classification Systems. *Tunnelling and Underground Space Technology*. 24(4), 491-492.
- Park, H. and West, T. R. (2001). Development of a Probabilistic Approach for Rock Wedge Failure. *Engineering Geology*. 59(3), 233-251.
- Pearson, K. (1895). Note on Regression and Inheritance in the Case of Two Parents. *Proceedings of the Royal Society of London*. 58(347-352), 240-242.

- Pettifer, G. S. and Fookes, P. G. (1994). A Revision of the Graphical Method for Assessing the Excavatability of Rock. *Quarterly Journal of Engineering Geology and Hydrogeology*. 27(2), 145-164.
- Piteau, D. R. (1973). Characterizing and Extrapolating Rock Joint Properties in Engineering Practice. *Rock Mechanics, Suppl. 2*, 5-31.
- Potts, E. L. J. and Shuttleworth, P. (1958). A Study on the Ploughability of Coal, with Special Reference to the Effects of Blade Shape, Direction of Planing to the Cleat, Planing Speed and the Influence of Water Infusion. *Transactions of the Institute of Mining Engineers*. 519–553.
- Price, D. G. (1993). A Suggested Method for the Classification of Rock Mass Weathering by a Ratings System. *Quarterly Journal of Engineering Geology and Hydrogeology*, 26(1), 69-76.
- Price, D. G. (1995). Weathering and Weathering Processes. *Quarterly Journal of Engineering Geology and Hydrogeology*. 28(3), 243-252.
- Price, N. J. (1981). *Fault and Joint Development in Brittle and Semi-brittle Rock*. Pergamon Press.
- Price, D. G. and de Freitas, M. H. (2009). *Engineering Geology: Principles and Practice*. Springer.
- Priest, S. D. and Hudson, J. A. (1976). Discontinuity Spacings in Rock. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics*. 13(5), 135-148.
- Priest, S. D. (1993). *Discontinuity Analysis for Rock Engineering*. Chapman & Hall.
- Pusch, R. (1995). *Rock Mechanics on a Geological Base*. Elsevier.
- Rabcewicz, L. V. (1964). The New Austrian Tunneling Method. *Water Power, Part One*. 16(11), 453-457.
- Rabcewicz, L. V. (1965). The New Austrian Tunneling Method. *Water Power, Part Two*. 16(12), 511-515.
- Rafek, A. G. and Goh, T. L. (2012). Correlation of Joint Roughness Coefficient (JRC) and Peak Friction Angles of Discontinuities of Malaysian Schists. *Earth Science Research*. 1(1), 57-63.
- Raj, J. K. (1985). Characterisation of the Weathering Profile Developed Over a Porphyritic Biotite Granite in Peninsular Malaysia. *Bulletin of the International Association of Engineering Geology - Bulletin de l'Association Internationale de Géologie de l'Ingénieur*. 32(1), 121-129.

- Raj, J. K. (2010). Soil-moisture Retention Characteristics of Earth Materials in the Weathering Profile Over a Porphyritic Biotite Granite. *American Journal of Geoscience*. 1(1), 12-20.
- Rajah S Senathi, Manickam K, Ismail bin Ngah Mat Yasin, Malaysia. Chung Sooi, Keong (1982). *Mineral Resources Map of Johor, Peninsular Malaysia*. Director-General of Geological Survey.
- Reichmuth, D. R. (1963). Correlation of Force-displacement Data with Physical Properties of Rock for Percussive Drilling Systems. *Proceedings of the 5<sup>th</sup> US Rock Mechanics Symposium*. University of Minnesota, USA, ed. C. Fairhurst, Pergamon Press, 33–59.
- Ritter, W. (1879). *Die Statik der Tunnelgewölbe*. Berlin: Springer.
- Robertson, A. M. (1988). Estimating Weak Rock Strength. *Proceedings of the SME Annual Meeting*. Tucson, Arizona, 1-5.
- Rocscience (2000). *Dips 5.0 Windows*. Rocscience Inc. Toronto, Ontario.
- Romana, M. (1985). New Adjustment Ratings for Application of Bieniawski Classification to Slopes. *Symposium on the Role of Rock Mechanics, ISRM*. Zacatecas, 49-53.
- Romana, M. and Vasarhelyi, B. (2007). A Discussion on the Decrease of Unconfined Compressive Strength Between Saturated and Dry Rock Samples. *The 11<sup>th</sup> Congress of ISRM, The Second Half Century of Rock Mechanics*. London, 139-142.
- Rostami, J. and Ozdemir, L. (1993). A New Model for Performance Prediction of Hard Rock TBMs. *Proceedings of Rapid Excavation and Tunnelling Conference*. USA, 794–809.
- Roxborough, F. F. (1987). The Role of Some Basic Rock Properties in Assessing Cuttability. *Proceedings of Seminar on Tunnels, Wholly Engineered Structures, Australian Federation of Civil Celebrants*. April. Canberra, Institution of Engineers Australia, 1-21.
- Roxborough, F. F and Philips, H. R. (1981). *Applied Rock and Coal Cutting Mechanics*. Australian Foundation Workshop Course 156/81.
- Roxborough, F. F. and Liu, Z. C. (1995). Theoretical Considerations on Pick Shape in Rock and Coal Cutting. *Proceedings of the 6<sup>th</sup> Underground Operator's Conference*. 13-14 November. Kalgoorlie, WA, Australia, 189-193.

- Ruxton, B. P. and Berry, L. (1957). Weathering of Granite and Associated Erosional Features in Hong Kong. *Bulletin of the Geological Society of America*. 68(10), 1263-1292.
- Sahimi, M. (2012). *Flow and Transport in Porous Media and Fractured Rock*. John Wiley & Sons.
- Saito, T. (1981). Variation of Physical Properties of Igneous Rocks in Weathering. In *ISRM International Symposium*. ISRM International Symposium, 21-24 September. Tokyo, Japan, 191-196.
- Santi, P. M. (1995). Assessing the Strength and Durability Properties of Shales. In Keefer, D. K. and Ho, C. L. (Eds.). *Landslides Under Static and Dynamic Conditions - Analysis, Monitoring and Mitigation*. (pp. 37-55). ASCE Geotechnical Special Publication No. 52.
- Santi, P. M. (2006). Field Methods for Characterizing Weak Rock for Engineering. *Environmental & Engineering Geoscience*. 12(1), 1-11.
- Sari, M., Karpuz, C. and Ayday, C. (2010). Estimating Rock Mass Properties Using Monte Carlo simulation: Ankara andesites. *Computers & Geosciences*. 36(7), 959-969.
- Sasaki, T., Kinoshita, S. and Ishijima, Y. (1981). A Study On Water-sensitivity of Argillaceous Rock. *ISRM International Symposium*. 21-24 September. Tokyo, Japan, 149-154.
- Scoble, M. J. and Muftuoglu, Y. V. (1984). Derivation of a Diggability Index for Surface Mine Equipment Selection. *Mining Science and Technology*. 1(4), 305-322.
- Singh, B. and Goel, R. K. (2011). *Engineering Rock Mass Classification: Tunnelling, Foundations and Landslides*. Elsevier Science.
- Singh, R. N., Denby, B., Egretli, I. and Pathon, A. G., (1986). Assessment of Ground Rippability in Opencast Mining Operations. *Mining Magazine, University of Nottingham*. 38, 21-34.
- Singh, R. N., Hassani, F. P. and Elkington, P. A. S. (1983). The Application of Strength and Deformation Index Testing to the Stability Assessment of Coal Measures Excavations. *Proceeding 24<sup>th</sup> US Symposium On Rock Mechanics*. June. Texas A&M University, 599-609.
- Slob, S., Hack, H. R. G. K. and Turner, A. K., (2002). An Approach to Automate Discontinuity Measurements of Rock Faces Using Laser Scanning

- Techniques. *Proceedings of ISRM EUROCK*. 25-28 November. Funchal, 87-94.
- Smith, H. J. (1986). Estimating Rippability by Rock Mass Classification. *Proceedings of the 27th U.S. Symposium on Rock Mechanics*. 23-25 June. Tuscaloosa, Alabama, 443-448.
- Song, J. J., (2006). Estimation of Areal Frequency and Mean Trace Length of Discontinuities Observed in Non-Planar Surfaces. *Rock Mechanics and Rock Engineering*. 39(2), 131-146.
- SPSS (2007). SPSS for Windows, Version 16.0. Chicago, SPSS Inc.
- Steffen, O. K. H., Kerrich, J. E. and Jennings, J. E. (1975). Recent Developments in Interpretation of Data From Joint Surveys in Rock Masses. *Proceeding 6<sup>th</sup> Regional Conference on Soil Mechanics and Foundation Engineering*. Durban, 17-26.
- Stille, H., Groth, T. and Fredriksson, A. (1982). FEM-analysis of Rock Mechanical Problems with JOBFEM. *BeFo och KTH*. Stockholm 307, 1/82.
- Summerfield, M. A. (1991). *Global Geomorphology*. Harlow: Longman.
- Taheri, A. (1978). *The Moisture Content Influence on the Mechanical Properties of Banter Sandstone*. MSc Thesis. Imperial College, London.
- Tajul Anuar Jamaluddin and Ismail Yusuf (2003). Influence of discontinuity on overbreaks and underbreaks in rock excavation- Case study from Beris Dam, Kedah, Malaysia. *Bulletin Geological Society of Malaysia*. 46, 75-85.
- Tajul Anuar Jamaluddin and Mogana S. (2000). Excavatability Assessment of Weathered Rock Mass-Case Study from Ijok, Selangor and Kemaman, Terengganu. *Warta Geologi*. 26(3), 93-94.
- Tatiya, R. R. (2005). *Surface and Underground Excavations: Methods, Techniques and Equipment*. London, UK: Taylor & Francis.
- Terzaghi, K. (1946). Introduction to Tunnel Geology in Rock Tunneling with Steel Supports. *Proctor and White, Commercial Shearing and Stamping Co*. Youngstown, Ohio.
- Terzaghi, R.D. (1965). Sources of Error in Joint Surveys. *Geotechnique*. 15(3), 287-304.
- Thuro, K. and Scholz, M. (2003). Deep Weathering and Alteration in Granites-A Product of Coupled Processes. *Proceedings of the International Conference on Coupled T-H-M-C Processes in Geosystems: Fundamentals, Modeling,*

- Experiments and Applications (GeoProc2003)*. 13-15 October. Royal Institute of Technology (KTH), Stockholm, Sweden, 2-6.
- Tugrul, A. (2004). The Effect of Weathering on Pore Geometry and Compressive Strength of Selected Rock Types From Turkey. *Engineering Geology*. 75(3-4), 215-227.
- Tugrul, A. and Gurpinar, O. (1997). A Proposed Weathering Classification for Basalts and Their Engineering Properties (Turkey). *Bulletin of the International Association of Engineering Geology*. 55(1), 139-149.
- Tugrul, A. and Zarif, I. H. (1999). Correlation of Mineralogical and Textural Characteristics with Engineering Properties of Selected Granitic Rocks from Turkey. *Engineering Geology*. 51(4), 303-317.
- Turk, N. and Dearman, W.R. (1986). Influence of Water on Engineering Properties of Weathered Rocks. *Geological Society, London, Engineering Geology Special Publications*. 3(1), 131-138.
- Unal, E. (1996). Modified Rock Mass Classification: M-RMR System. Milestones in Rock Engineering, the Bieniawski Jubilee Collection. Rotterdam: Balkema. 203-223.
- Valantine, A. (1973). An Examination of the Various Conventional Procedures to Determine the Resistance of Rock to Mechanized Winning. *Development and Exploratory Techniques in Coal Mines, Commission of the European Communities*. November. Luxemburg, 177-193.
- Vardakos, S. (2004). A Rock Mass Classification Tool for Personal Digital Assistants. The Charles E. Via Jr. Department of Civil and Environmental Engineering. Geotechnical Engineering Group. Blacksburg, Virginia.
- Vargas, M. (1953). Some Engineering Properties of Residual Clay Soils Occurring in Southern Brazil. *Proceedings of the 3<sup>rd</sup> International Conference on Soil Mechanics and Foundation Engineering*. Zurich, 259-268.
- Vasarhelyi, B. and Van, P. (2006). Influence of Water Content on the Strength of Rock. *Engineering Geology*. 84(1-2), 70-74.
- Vutukuri, V. S., Lama, R. D. and Suluja S. S. (1974). *Handbook on Mechanical Properties of Rocks*. ( 1<sup>st</sup> ed.). The University of Virginia: Trans Tech. Publications.
- Wallis, R. F. and King, M. S. (1980). Discontinuity Spacings in a Crystalline Rock. *International Journal of Rock Mechanics and Mining*. 17(1), 63-66.

- Weaver, J. M. (1975). Geological Factors Significant in the Assessment of Rippability. *The Civil Engineering in South Africa*. 17(12), 313–316.
- Weiss, M. (2008). Techniques for Estimating Fracture Size: A Comparison of Methods. *International Journal of Rock Mechanics and Mining Sciences*. 45(3), 460-466.
- West, G. (1981). A Review of Rock Abrasiveness Testing for Tunneling. *Proceeding of the International Symposium on Weak Rock*. 21-24 September. Tokyo, 585-594.
- Wickham, G. E., Tiedeman, H. R. and Skinner, E. H. (1972). Support Determination Based on Geologic Predictions. *Proceeding of the North American Rapid Excavation and Tunneling Conference, American Society of Mechanical Engineerings*. New York, 43-64.
- Williamson, D. A. (1984). Unified Rock Classification System. *Bulletin of the Association of Engineering Geologists*. 21(3), 345-354.
- Zadhesh, J., Jalali, S. M. E. and Ramezanzadeh, A. (2013). Estimation of Joint Trace Length Probability Distribution Function in Igneous, Sedimentary and Metamorphic Rocks. *Arabian Journal of Geosciences*. 1-9. doi: 10.1007/s12517-013-0861-1.
- Zianab Mohamed (2004). *Engineering Characterization of Weathered Sedimentary Rock for Engineering Work*. Unpublished PhD thesis. National University of Malaysia.
- Zhang, L. (2005). *Engineering Properties of Rocks* [electronic resource]: Elsevier Science Limited.
- Zhao, J., Broms, B. B., Zhou, Y. and Choa, V. (1994). A Study of the Weathering of the Bukit Timah Granite Part A: Review, Field Observations and Geophysical Survey. *Bulletin of the International Association of Engineering Geology*. 49(1), 97-106.