

QUARRY BLAST EVALUATION SYSTEM FOR ROCK FRAGMENTATION

MUHAMMAD IRFAN BIN SHAHRIN

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy

School of Civil Engineering
Faculty of Engineering
Universiti Teknologi Malaysia

NOVEMBER 2020

DEDICATION

This thesis is dedicated to;

My UTM supervisor,
Ir. Dr. Rini Asnida binti Abdullah

My Parents,
Shahrin Mohammad & Zurina Ramly / Amran Mohd Sam & Rohana Tohak

My wife (Amira Huda), daughter (Hana Inara), family and all my dear friends

I have been extremely fortunate to have been brought up by them, who instilled in me the desire to continue my education. Without their help and support, this research would not have been possible.

Thank you for your prayers, attention and spiritual support

ACKNOWLEDGEMENT

In the name of Allah, the most Gracious and the Most Merciful

Alhamdulillah and praise to Allah SWT for enabling me to complete the thesis.

I am extremely grateful to my supervisor, Ir. Dr. Rini Asnida binti Abdullah for his enthusiastic and expertise guidance, constructive suggestions, encouragement and valuable assistance in many ways. Also, I am very thankful to him for sharing his precious time to view this thesis. This research would not have been what it is without such assistance.

I am also deeply indebted to my co-supervisor, Dr. Radzuan bin Sa'ari and Prof. Seokwon Jeon for his suggestions and encouragement to help me during the study and during the preparation of this research.

Many thanks are extended to Geotechnical Laboratory staff members for their enthusiasm and willingness to help throughout the project.

It is my pleasure to thank my fellow friends for their support and contribution to make this project a success. I would also like to acknowledge the contributions of those who have helped either directly or indirectly in the completion of this project.

Finally, I would like to express my sincere appreciation to my parents and family for their endless support, encouragement and patience throughout the duration of this research.

Thank you

ABSTRACT

Blasting produces energy to fragment the rock mass in mining, quarry and civil engineering projects. In mining and quarrying operation, blasting aims to extract the largest possible quantity of rock at minimum cost in the safest manner with minimum side effects such as ground vibration, flyrock and noise. Hence, blast design plays a vital role. Poor blast design is harmful to the surrounding and the desired rock fragmentation cannot be obtained. It affects the drilling and blasting cost as well as the efficiency of all the subsystems such as loading, hauling and crushing in mining operations. Therefore, this research aims to evaluate the significant parameters related to the blasting operation and establish a blast design model for better prediction of particle size of rock fragmentation. The study will focus on the granite quarry operation. Terrestrial and aerial survey technology namely Terrestrial Laser Scanning (TLS) and Unmanned Aerial Vehicle (UAV) respectively, are carried out during pre and post of the blasting for discontinuity mapping. Then the engineering properties of the rock are determined through the laboratory work. These properties are then utilised in Discrete Element Method (DEM) numerical simulation using Bonded Particle Method (BPM) and Particle Blast Method (PBM) to predict the blasting performance. Once the model is verified, the influencing parameters are further investigated through a series of parametric study on rock fragmentation. The parameters involved are burden, spacing, stemming, hole diameter, bench height and powder factor. The relationship between the spacing to burden (S/B) ratio, stemming to burden (T/B) ratio, burden to hole diameter (B/D) ratio, bench height to burden (BH/B) ratio and powder factor against the predict mean particle size (d_{50}) and uniformity index (n) is studied. Furthermore, a machine learning algorithm is utilized to predict the d_{50} , sieve size at 80% material passing (d_{80}) and parameters n as the output product. MATLAB and RapidMiner software of machine learning algorithms with four different learnings, which are Linear Regression, Decision Tree, Random Forest and Support Vector Machine (SVM), are utilised in this study. Comparisons of the output predictions between the learning algorithms are conducted and the influential parameters for the predictions are identified. The results show that Random Forest learning is chosen as the best machine learning, since the results obtained show the highest R-squared value, with the lowest Root Mean Square Error (RMSE) value. The best R-squared and RMSE results for prediction of mean particle size are 0.85 and 0.046, respectively. In addition, the best R-Squared and RMSE results for prediction of uniformity index are 0.75 and 0.324, respectively. A quarry blast evaluation system for prediction of rock fragmentation was developed. The blast evaluation system and prediction for rock fragmentation developed is focused on open pit quarry but this also may be applicable to rock slope. The blasting evaluation system established in this study will be very beneficial to policymakers, practitioners and designers associated with quarry blasting for a safe quarry blasting operation. Hence this will help the engineer to make crucial decisions during the planning, design and operational stages of a quarry.

ABSTRAK

Pembedilan menghasilkan tenaga untuk memecahkan batuan dalam projek perlombongan, kuari dan kejuruteraan awam. Dalam operasi perlombongan dan kuari, pembedilan bertujuan untuk mengekstrak batu dalam kuantiti yang maksimum dengan cara yang selamat dan kesan sampingan yang minimum seperti getaran darat, batu terbang dan pencemaran bunyi. Oleh itu, reka bentuk bedilan memainkan peranan penting dalam aktiviti tersebut. Kelemahan pada reka bentuk bedilan membahayakan kawasan sekeliling dan saiz serpihan batu yang diingini tidak dapat diperolehi. Selain itu, ia juga memberi kesan kepada kos penggerudian dan bedilan serta kesan kepada kecekapan subsistem dalam operasi perlombongan seperti memuat, mengangkut dan menghancurkan. Tujuan penyelidikan ini adalah untuk menilai parameter penting yang berkaitan dengan operasi bedilan dan juga menghasilkan model reka bentuk bedilan untuk ramalan saiz pecahan batu yang lebih baik. Kajian ini memberi tumpuan kepada operasi kuari granit. Tinjauan geomatik dan tinjauan teknologi udara iaitu pengimbasan laser terrestrial dan kenderaan udara tanpa kawalan dilakukan sebelum dan selepas letupan untuk pemetaan ketakselajaran. Kemudian, sifat kejuruteraan batu diperolehi dari kerja makmal. Ia kemudiannya digunakan dalam simulasi alat pengiraan element diskret dengan menggunakan kaedah ikatan partikel (BPM) dan kaedah bedilan partikel (PBM) untuk meramal prestasi bedilan. Setelah model ini telah disahkan, parameter yang mempengaruhi pemecahan batu akan dikaji secara lebih mendalam melalui satu siri kajian parametrik. Parameter yang terlibat adalah beban, jarak, ketinggian sumbatan, diameter lubang bedilan, tinggi tingkatan dan faktor serbuk. Hubungan antara nisbah jarak dan beban (S/B), ketinggian sumbatan dan beban (T/B), beban dan diameter lubang bedilan (B/D), tinggi tingkatan dan beban (BH/B) dan faktor serbuk terhadap meramal min saiz batu (d_{50}) dan keseragaman indeks (n) telah dikaji. Tambahan pula, algoritma pembelajaran mesin digunakan untuk meramal d_{50} , 80% lepasan saiz ayak (d_{80}), parameter n sebagai produk keluaran. Algoritma pembelajaran mesin dalam perisian MATLAB dan RapidMiner dengan empat pembelajaran yang berbeza iaitu Regresi Lelurus, Akar Pokok Keputusan, Hutan Rawak, Mesin Vektor Sokongan digunakan dalam kajian ini. Perbandingan ramalan keluaran antara algoritma pembelajaran dijalankan dan parameter yang paling berpengaruh untuk ramalan telah dikenalpasti. Hasil kajian mendapati bahawa pembelajaran Hutan Rawak adalah pembelajaran terbaik kerana hasil yang diperolehi menunjukkan nilai R-kuadrat tertinggi dan nilai min ralat kuasa dua (RMSE) terendah. Nilai R-kuadrat dan RMSE yang terbaik untuk ramalan min saiz batu masing-masing ialah 0.85 dan 0.046. Manakala, nilai R-kuadrat dan RMSE yang terbaik masing-masing untuk ramalan keseragaman indeks ialah 0.75 dan 0.324. Sistem penilaian bedilan kuari untuk ramalan pecahan batu telah dibangunkan. Sistem penilaian bedilan kuari yang telah dibangunkan itu difokuskan untuk kuari lubang terbuka, akan tetapi ia juga mungkin sesuai untuk cerun batu. Sistem bedilan yang dibangunkan dalam kajian ini akan memberi manfaat kepada penggubal dasar, pengamal dan pereka yang berkaitan dengan operasi pembedilan, untuk operasi pembedilan yang selamat. Selain itu, model ramalan akan membantu jurutera dalam membuat keputusan penting semasa perancangan, rekabentuk dan peringkat operasi sesuatu kuari.

TABLE OF CONTENTS

	TITLE	PAGE
	DECLARATION	iii
	DEDICATION	iv
	ACKNOWLEDGEMENT	v
	ABSTRACT	vi
	ABSTRAK	vii
	TABLE OF CONTENTS	viii
	LIST OF TABLES	xv
	LIST OF FIGURES	xviii
	LIST OF ABBREVIATIONS	xxvii
	LIST OF SYMBOLS	xxix
	LIST OF APPENDICES	xxxii
CHAPTER 1	INTRODUCTION	1
1.1	Background of Study	1
1.2	Problem Statement	2
1.3	Objectives of Study	4
1.4	Scope of Study	5
1.5	Significance of Study	6
1.6	Thesis outline	6
CHAPTER 2	LITERATURE REVIEW	9
2.1	Introduction	9
2.2	Blast Mechanism	11
2.3	Parameters that Influence Blast Results	13
2.3.1	Uncontrollable Parameters	15
2.3.1.1	Properties of Rock Mass and Discontinuities	15
2.3.1.2	Geo-mechanical Characteristics of the Intact Rock	17

2.3.2	Controllable Parameters	18
2.3.2.1	Blast Design Parameters	19
2.3.2.2	Explosive Charge Characteristics	22
2.4	Rock Mass Classification	23
2.4.1	Rock Mass Rating (RMR)	24
2.4.2	Geological Strength Index (GSI)	25
2.5	Blastability Index (BI)	27
2.6	Field Data Acquisition Methods	31
2.6.1	Total Station	31
2.6.2	Terrestrial Laser Scanning (TLS)	32
2.6.3	Photogrammetry	35
2.6.4	Comparison between Data Acquisition Methods	37
2.7	Blast Results	38
2.7.1	Rock Fragmentation	40
2.7.2	Flyrock	41
2.7.3	Ground Vibration	41
2.7.4	Air-blast	43
2.8	Methods to Predict Rock Fragmentation	44
2.8.1	Empirical Method	45
2.8.2	Mechanistic Method	49
2.8.3	Numerical Method	50
2.8.3.1	Soft Computational Techniques	50
2.8.3.2	Data Used for Model Development	52
2.8.3.3	Numerical Simulation	54
2.8.4	Advantages and Limitations using Prediction Methods	56
2.9	Discrete Element Method (DEM) and Bonded Particle Method	57
2.10	Particle Blast Method (PBM)	61
2.11	Machine Learning	63
2.11.1	Linear Regression	63
2.11.2	Decision Tree	64

2.11.3	Support Vector Machines (SVM)	65
2.11.4	Random Forest	65
2.11.5	Comparison of Learning Methods	66
2.12	Summary	67
CHAPTER 3	METHODOLOGY	71
3.1	Introduction	71
3.1.1	PHASE 1: Preliminary Investigation and Fieldwork	72
3.1.2	PHASE 2: Numerical Modeling and Parametric Study	73
3.1.3	PHASE 3: Establish a Machine Learning Model	74
3.2	Quarry Background Information	75
3.2.1	Location and Accessibility	76
3.2.2	Quarry Geology	77
3.3	Field Data Collection	79
3.3.1	Rock Blasting Area	79
3.3.2	Blasting Design	80
3.3.3	Established Ground Control Points (GCP) using Static GPS and Rock Surface Scanning using TLS	81
3.3.4	Rock Surface Mapping using UAV	84
3.4	TLS and UAV Data Processing	86
3.4.1	TLS Data Processing	87
3.4.2	Discontinuities Measurement based on TLS Pre Blast Point Cloud Data	89
3.4.3	UAV Data Processing	92
3.4.4	Combine Point Cloud Data from Post Blast TLS and UAV for Rock Fragmentation Analysis	94
3.4.5	Digital Image Processing	95
3.5	Laboratory Testing of Rock	100
3.5.1	Sample Preparation	102
3.5.2	Index Test and Indirect Strength Test	103

3.5.2.1	Density Test (Saturation and Buoyancy Method)	104
3.5.2.2	Rebound Hammer Test (Schmidt)	105
3.5.2.3	Ultrasonic Velocity Test	107
3.5.2.4	Point Load Test	108
3.5.2.5	Tensile Strength Test (Brazilian test)	110
3.5.3	Direct Strength Test	112
3.5.3.1	Uniaxial Compression Test (UCT)	112
3.5.3.2	Triaxial Compression Test	114
3.5.3.3	Direct Shear Test	117
3.6	Numerical Model	122
3.6.1	Calibrating Intact Specimens	122
3.6.1.1	Convergence Effect	130
3.6.1.2	Uniaxial Compression Test	132
3.6.1.3	Tensile Strength Test (Brazilian)	133
3.6.2	Calibrating Bench Blast Model	134
3.7	Parametric Study	136
3.8	Prediction of Rock Fragmentation Characteristics using Machine Learning	137
3.8.1	MATLAB Software	140
3.8.1.1	Linear Regression	142
3.8.1.2	Decision Tree	143
3.8.1.3	Support Vector Machines (SVM)	144
3.8.1.4	Random Forest	145
3.8.2	RapidMiner Software	145
3.8.2.1	Linear Regression	149
3.8.2.2	Decision Tree	149
3.8.2.3	Support Vector Machines (SVM)	149
3.8.2.4	Random Forest	150
3.8.3	Summary of Learning Input Parameters	150
3.8.4	Cross-Validation	151

3.9	Concluding Remarks	152
CHAPTER 4	FIELD DATA ANALYSIS AND LABORATORY TESTING FOR ROCK MASS CLASSIFICATION	153
4.1	Introduction	153
4.2	GCPs, TLS and UAV Data Assessment	153
4.2.1	GCP Measurement Accuracy using Static GPS	153
4.2.2	TLS Point Cloud (Pre & Post Blasting) Accuracy Assessment	154
4.2.3	Pre-Blast TLS Point Cloud Discontinuity Measurement Results	156
4.2.4	UAV Point Cloud Modeling	162
4.2.5	Hybrid Point Cloud Data	164
4.2.6	Digital Image Processing	168
4.3	Laboratory Testing of Rock	169
4.3.1	Index Test and Indirect Strength Test	169
4.3.1.1	Density Test (Saturation and Buoyancy Method)	169
4.3.1.2	Rebound Hammer Test (Schmidt hammer)	170
4.3.1.3	Ultrasonic Velocity Test	171
4.3.1.4	Point Load Test	172
4.3.1.5	Indirect Tensile Strength Test (Brazilian test)	173
4.3.2	Direct Strength Test	174
4.3.2.1	Uniaxial Compression Test	175
4.3.2.2	Triaxial Compression Test	179
4.3.2.3	Direct Shear Test	182
4.3.3	Summary of Laboratory Test	187
4.4	Rock Mass Classification	188
4.5	Summary	192
CHAPTER 5	NUMERICAL SIMULATION	193
5.1	Introduction	193
5.2	Numerical Model	193

5.2.1	Calibrating Intact Specimen	194
5.2.1.1	Relationship between micro and macro properties	194
5.2.1.2	Convergence Effect	198
5.2.1.3	Uniaxial Compression Test	200
5.2.1.4	Indirect Tensile Strength Test (Brazilian Test)	203
5.2.2	Calibration of Rock Mass Model	206
5.2.2.1	Bench Blasting Model	206
5.2.2.2	Digital Image Processing	208
5.3	Parametric Study	211
5.3.1	Spacing to Burden Ratio	212
5.3.2	Stemming to Burden Ratio	216
5.3.3	Burden to Hole Diameter Ratio	220
5.3.4	Bench Height to Burden Ratio (Stiffness)	223
5.3.5	Powder Factor	226
5.4	Summary	229
CHAPTER 6	MACHINE LEARNING PREDICTION	231
6.1	Introduction	231
6.2	Prediction of Rock Fragmentation Characteristics using Machine Learning	231
6.2.1	Mean Particle Size (d_{50})	232
6.2.1.1	Data Set 1	232
6.2.1.2	Data Set 2	237
6.2.2	Sieve Size at 80% Material Passing (d_{80})	239
6.2.2.1	Data Set 1	239
6.2.2.2	Data Set 2	241
6.2.3	Uniformity Index (n)	243
6.2.3.1	Data Set 1	243
6.2.3.2	Data Set 2	245
6.2.4	Comparison Results	247
6.3	Summary	256

CHAPTER 7	CONCLUSION AND RECOMMENDATIONS	257
7.1	Introduction	257
7.2	Research Outcomes	257
7.3	Contributions to Knowledge	260
7.4	Recommendations for Future Work	263
REFERENCES		264
LIST OF PUBLICATIONS		287

LIST OF TABLES

TABLE NO.	TITLE	PAGE
Table 2.1	Different types of accidents at quarry sites in Malaysia from Department of Occupational Safety and Health (DOSH)	10
Table 2.2	Rock mass classification	25
Table 2.3	Blastability index description of ease of blasting (Chatziangelou and Christaras, 2017)	28
Table 2.4	Blastability quality system for widely spaced discontinuities (Chatziangelou and Christaras, 2015)	30
Table 2.5	Comparison of data acquisition methods	38
Table 2.6	Safe level blasting criteria: threshold PPV values at different frequencies (USBM, DIN 4150, SS 460 48 66 and 87/70558)	43
Table 2.7	Parameters used in empirical rock fragmentation model	46
Table 2.8	Advantages and limitations of prediction methods	57
Table 2.9	Bond parameter card *DEFINE_DE_BOND in LS-DYNA (Tannu, 2017)	61
Table 2.10	Comparison of learning methods in Machine Learning	66
Table 2.11	Parameters used in the previous study	70
Table 3.1	Blast design parameters and explosive charge characteristics used in blasting	81
Table 3.2	List of ground control points coordinate	93
Table 3.3	Summary of laboratory testing	101
Table 3.4	Usability of rock parameters in this study	102
Table 3.5	Input properties and its range for calibration	128
Table 3.6	Investigate relationship between PBS_S / PBN_S and macro properties	128
Table 3.7	Investigate relationship between SFA & MAXGAP and macro properties	129
Table 3.8	Investigate relationship between PBS and macro properties	129

Table 3.9	Input parameters of different mesh type for convergence effect	131
Table 3.10	Intact rock properties selection for analysis in LS-DYNA	133
Table 3.11	Input parameters for borehole bench blast model	136
Table 3.12	Particle parameters of high explosive	136
Table 3.13	Range parameters of parametric study	137
Table 3.14	Learning input parameters for MATLAB software	150
Table 3.15	Learning input parameters for Rapidminer software	151
Table 4.1	TLS GCPs accuracy via GPS static observation	154
Table 4.2	TLS mean target error to back sight	155
Table 4.3	Accuracy assessment of TLS discontinuity measurement	156
Table 4.4	Joint spacing results obtained from point cloud data	157
Table 4.5	Joint length results obtained from point cloud data	158
Table 4.6	Summary of discontinuity length and spacing	159
Table 4.7	Data of dip and dip direction from point cloud data	160
Table 4.8	Mean dip and dip direction of joint sets	161
Table 4.9	UAV GCPs error	163
Table 4.10a	Baseline measurement using TLS point cloud data	166
Table 4.11	Summary of density test result	169
Table 4.12	Rebound number readings	170
Table 4.13	Summary of ultrasonic velocity test result	172
Table 4.14	Summary of point load test result	172
Table 4.15	Summary of Brazilian test result	173
Table 4.16	Summary of uniaxial compression test result	175
Table 4.17	Summary of triaxial compression test result	181
Table 4.18	Summary of shear test result	183
Table 4.19	Properties of granite intact specimen in the GGSB quarry	187
Table 4.20	Summary of rock mass rating score for the blast surface	190
Table 4.21	Geological strength index score for the blast surface (Marinos and Hoek, 2000)	190

Table 4.22	Blastability quality system score for the blast surface (Chatziangelou and Christaras, 2015)	191
Table 5.1	Results of relationship between PBS_S / PBN_S and macro properties	194
Table 5.2	Results of relationship between SFA & MAXGAP and macro properties	196
Table 5.3	Results of relationship between PBS and macro properties	197
Table 5.4	Input parameters of the calibrated model	200
Table 5.5	Comparison of UCS and E value between UCT DEM/BPM model and laboratory test	202
Table 5.6	Input parameters of the calibrated model	203
Table 5.7	Comparison of tensile strength and maximum tensile strain value between Brazilian DEM/BPM model and laboratory test	204
Table 5.8	Comparison of particle size distribution results	211
Table 5.9	Parametric study summary of T/B ratio using numerical simulations	216
Table 5.10	Relationship between blast design parameters and rock fragmentation characteristics	229
Table 6.1	Performance indices comparison between the software for prediction of Set 1 d_{50}	235
Table 6.2	Performance indices comparison between the software for prediction of Set 2 d_{50}	238
Table 6.3	Performance indices comparison between the software for prediction of Set 1 d_{80}	240
Table 6.4	Performance indices comparison between the software for prediction of Set 2 d_{80}	242
Table 6.5	Performance indices comparison between the software for prediction of Set 1 uniformity index	244
Table 6.6	Performance indices comparison between the software for prediction of Set 2 uniformity index	245
Table 6.7	Output prediction for Set 1 testing data	254
Table 6.8	Output prediction for Set 2 testing data	254
Table 6.9	Ranking summary of influential parameters for prediction of rock fragmentation characteristics	255
Table 6.10	A matrix correlation between parameters	255

LIST OF FIGURES

FIGURE NO.	TITLE	PAGE
Figure 2.1	Blast mechanism (Wyllie and Mah, 2017; Tatiya, 2017)	13
Figure 2.2	Categorisation of parameters that influencing the blast results modified after Bakhtvar <i>et al.</i> (2014).	14
Figure 2.3	Uncontrollable parameters (Hutchinson and Diederichs, 1996)	15
Figure 2.4	Blast design parameters applied in the quarry	19
Figure 2.5	Geological Strength Index	27
Figure 2.6	Example of Leica total station model (Leica TDRA6000)	32
Figure 2.7	Topcon GLS-2000 TLS	33
Figure 2.8	Measurement principles of different TLS systems: (A) time-of-flight; (B) phase-based (Smith, 2015)	34
Figure 2.9	Schematic illustration of the wave form digitizer EDM method (Maar and Zogg, 2014)	34
Figure 2.10	Flow of continuous optimisation of the blasting process	39
Figure 2.11	Recommended safe levels for blasting vibration from the USBM RI 8507 (Siskind <i>et al.</i> , 1980)	42
Figure 2.12	Types of rock fragmentation prediction method	44
Figure 2.13	Illustration of contact bond between particles (Flores-Johnson <i>et al.</i> , 2016)	59
Figure 2.14	Illustration of bonded particles (Flores-Johnson <i>et al.</i> , 2016)	59
Figure 2.15	Particle blast method (Teng and Wang, 2014)	62
Figure 3.1	Flow chart of research methodology	71
Figure 3.2	Flow chart of Phase 1	72
Figure 3.3	Flow chart of Phase 2	73
Figure 3.4	Flow chart of Phase 3	75
Figure 3.5	The location of GGSB quarry (a) Location of GGSB quarry in Malaysia map, (b) Quarry site from aerial view (Source: Google earth)	76

Figure 3.6	Quarry face panoramic view from north-east	77
Figure 3.7	Geology of Gemencheh area, Negeri Sembilan after Nasiman <i>et al.</i> (1996)	78
Figure 3.8	Geological map of Gemencheh area, Negeri Sembilan after Tate <i>et al.</i> (2008)	78
Figure 3.9	Rock blasting area (a) Total bench in Gemencheh quarry, (b) Location of rock blasting area at Gemencheh quarry	80
Figure 3.10	Blast sequence	80
Figure 3.11	Static GPS (a) Topcon Hyper II GPS Receiver, (b) GPS Static observation during fieldwork.	82
Figure 3.12	Location of TLS GCPs established using GPS via static observations	83
Figure 3.13	Procedures of TLS Topcon GLS 2000 scanning setup prior to scanning process.	84
Figure 3.14	Terrestrial Laser Scanning (a) Set-up and Configuration, (b) Prism used as TLS backsight target reference point.	84
Figure 3.15	UAV setups and mission planning preparation	85
Figure 3.16	Unmanned Aerial Vehicle (UAV) (a) DJI S1000 UAV used in this study, (b) DJI S1000 UAV Configuration and Gyro Calibration	85
Figure 3.17	TLS point cloud data processing procedure	87
Figure 3.18	List of TLS occupied station and backsight target coordinate	88
Figure 3.19	Command to assign image colour to point cloud	88
Figure 3.20	Selection of point clouds rock blasting area	89
Figure 3.21	Discontinuities measurement procedure	90
Figure 3.22	Draw reference line for discontinuities measurement	90
Figure 3.23	Identify joints for discontinuities measurement	91
Figure 3.24	UAV data processing procedure	92
Figure 3.25	Blast area orthophoto selection	92
Figure 3.26	GCPs location on the ground	93
Figure 3.27	Flowchart of the methodology data acquisition and processing used for rock fragmentation analysis	94

Figure 3.28	Pre and post blasting of rock surface (a) Pre blasting, (b) Post blasting	96
Figure 3.29	Image of fragment rock induced by blasting for calculation of size distribution (a) Fieldwork rock pile from digital camera and (b) Fieldwork rock pile from point cloud	97
Figure 3.30	The rock fragment identified manually (a) Fieldwork rock pile from digital camera and (b) Fieldwork rock pile from point cloud	98
Figure 3.31	Scaled object in the image (a) Fieldwork rock pile from digital camera and (b) Fieldwork rock pile from point cloud	99
Figure 3.32	Kuz – Ram Prediction	100
Figure 3.33	Sample preparation (a) Rock sample coring, (b) Rock sample cutting, (c) Lapping of core samples	103
Figure 3.34	Density test – buoyancy method (a) Vacuum desiccator, (b) Immersion bath with wire basket	105
Figure 3.35	Schmidt’s hammer	106
Figure 3.36	Calibration of Schmidt’s hammer before testing	106
Figure 3.37	Rock block of tested samples	106
Figure 3.38	Ultrasonic velocity test (a) Calibration test, (b) Granite rock testing	108
Figure 3.39	Rock specimen for point load test	109
Figure 3.40	MATEST point load test equipment	109
Figure 3.41	Apparatus for Brazilian Test (Tensile Strength Test)	110
Figure 3.42	Cradle for disc sample	110
Figure 3.43	Intact rock samples for testing	111
Figure 3.44	Brazilian test equipment	111
Figure 3.45	Intact rock specimens for testing	113
Figure 3.46	Rock specimens for UCT with vertical and horizontal strain gauge	113
Figure 3.47	Uniaxial compression testing equipment	114
Figure 3.48	Intact rock samples for testing	115
Figure 3.49	Universal testing machine and confining pressure generator used for triaxial compression test	116

Figure 3.50	Hoek's cell and Latex membrane	116
Figure 3.51	Test set-up for triaxial compression test with Hoek cell	116
Figure 3.52	Shear plane and core axis	118
Figure 3.53	Cross-sectional area of sample	118
Figure 3.54	Rock sample clamped for casting process	119
Figure 3.55	Casting process of rock sample in the mould	119
Figure 3.56	General set-up for direct shear strength testing of rock	120
Figure 3.57	Direct shear test equipment	120
Figure 3.58	Barton comb profilometer	121
Figure 3.59	Flow of intact specimen's calibration process	124
Figure 3.60	Rock sample and steel plates model	125
Figure 3.61	Disc sphere generation	126
Figure 3.62	Define material	126
Figure 3.63	Define parts	126
Figure 3.64	DEFINE_DE_BOND keyword	127
Figure 3.65	CONTROL_DISCRETE_ELEMENT keyword	127
Figure 3.66	DEFINE_DE_TO_SURFACE_COUPLING keyword	129
Figure 3.67	BOUNDARY_SPC_SET keyword	130
Figure 3.68	BOUNDARY_PRESCRIBED_MOTION_SET keyword	130
Figure 3.69	Models with different mesh types for convergence mesh (a) Super fine mesh (b) Fine mesh (c) Normal mesh (d) Coarse mesh (e) Super coarse mesh	131
Figure 3.70	UCT of granite sample (a) experimental test and (b) numerical simulation	133
Figure 3.71	Brazilian test of granite sample (a) experimental test and (b) numerical simulation	134
Figure 3.72	One borehole bench blast model (a) Geometry of bench blast model and (b) Bench blast model using DEM/BPM	135
Figure 3.73	Total data number used in machine learning	139
Figure 3.74	Input and output variables in machine learning	139
Figure 3.75	MATLAB and RapidMiner software of machine learning algorithms with four different learning's	139

Figure 3.76	Machine learning process	139
Figure 3.77	Select attributes and setup validation in MATLAB	141
Figure 3.78	Overview of MATLAB Regression learner application	141
Figure 3.79	Steps for new prediction in MATLAB	142
Figure 3.80	Linear Regression model in regression learner MATLAB	143
Figure 3.81	Decision Tree model in regression learner MATLAB	144
Figure 3.82	SVM model in regression learner MATLAB	144
Figure 3.83	Random Forest model in regression learner MATLAB	145
Figure 3.84	Interface of RapidMiner	146
Figure 3.85	RapidMiner process of different learnings	147
Figure 3.86	Select attributes in RapidMiner	147
Figure 3.87	Example of cross validation process	148
Figure 3.88	RapidMiner Prediction process	148
Figure 3.89	A graphical representation of how cross-validation works	152
Figure 4.1	TLS point cloud (a) pre and (b) post blasting	155
Figure 4.2	Estimation of discontinuity spacing for three joint sets	158
Figure 4.3	Estimation of discontinuity length for three joint sets	159
Figure 4.4	Contour plot analysis using Dips software	161
Figure 4.5	Mean set planes obtained using Dips software	161
Figure 4.6	UAV flight plane and camera location	163
Figure 4.7	UAV point cloud (a) pre and (b) post blasting	163
Figure 4.8	Post blasting point cloud (a) TLS (b) UAV	164
Figure 4.9	Accuracy measurement of post blast point cloud (a) TLS (b) UAV	166
Figure 4.10	Hybrid for estimation of rock fragmentation distribution	167
Figure 4.11	Fieldwork Rock Fragmentation Distribution	168
Figure 4.12	Uniaxial compressive strength and Schmidt hammer rebound number relationship (after Deere and Miller 1966)	171
Figure 4.13	Typical failure mode behaviour of Brazilian test (Basu <i>et al.</i> , 2013)	174

Figure 4.14	Sample modes of failure after Brazilian test (a) Sample B1, (b) Sample B2, (c) Sample B3, and (d) Sample B4	174
Figure 4.15	Typical failure mode behaviour of uniaxial compression test (Basu <i>et al.</i> , 2013)	175
Figure 4.16	Sample modes of failure after UCT (a) Sample UC 1, (b) Sample UC 2, (c) Sample UC 3, (d) Sample UC 4 and (e) Sample UC 5	176
Figure 4.17	Failure mode under uniaxial compressive strength test	177
Figure 4.18	Graph of Axial stress vs Axial strain	178
Figure 4.19	Graph of UCT uniaxial stress vs strain with strain gauge for UC 5	179
Figure 4.20	Sample modes of failure after triaxial test (a) Sample TC1, (b) Sample TC2, and (c) Sample TC3	180
Figure 4.21	Failure mode under Triaxial compression test	180
Figure 4.22	Graph Axial stress vs Axial strain	181
Figure 4.23	Mohr's circles and the Mohr-Columb failure envelope for Triaxial compression test	182
Figure 4.24	Graph shear stress versus horizontal displacement	183
Figure 4.25	Comparison between graph shear stress vs normal stress and roughness profile of Sample DS 2	184
Figure 4.26	Shear stress versus normal stress	184
Figure 4.27	Laboratory scale joint roughness profiles with their measured JRC values	185
Figure 4.28	Estimation of JRC value for top Sample 1	186
Figure 4.29	Estimation of JRC value for bottom Sample 1	186
Figure 4.30	Shear stress versus normal stress	186
Figure 4.31	Iron stained surface	189
Figure 4.32	Very blocky	189
Figure 4.33	Rough surface	189
Figure 5.1	Graph axial stress vs axial strain with different PBS_S / PBN_S	195
Figure 5.2	Graph relationship between PBS_S / PBN_S and Young's modulus	195

Figure 5.3	Graph axial stress vs axial strain with different SFA & MAXGAP	196
Figure 5.4	Graph relationship between SFA & MAXGAP and Young's modulus	197
Figure 5.5	Graph relationship between PBS and Particle strain ratio (P_{sr})	198
Figure 5.6	Comparison UCT DEM/BPM model with different mesh size	199
Figure 5.7	Comparison uniaxial compressive strength of different mesh UCT DEM/BPM model	199
Figure 5.8	Comparison of UCT test in (a) Numerical model before testing, (b) Mode of failure in numerical model and (c) Laboratory test	201
Figure 5.9	Comparison UCT DEM/BPM model with experimental data of granite specimen	202
Figure 5.10	Comparison of Brazilian test in (a) Numerical before testing, (b) Numerical after testing and (c) Laboratory test	205
Figure 5.11	Comparison Brazilian DEM/BPM model with experimental data of granite specimens	205
Figure 5.12	Bench blasting model from a sectional view	206
Figure 5.13	Simulated bench blasting process in sectional view (a) $t = 0$ ms, (b) $t = 0.5$ ms, (c) $t = 2$ ms, (d) $t = 5$ ms, (e) $t = 10$ ms, (f) $t = 30$ ms	207
Figure 5.14	Blast mechanism in numerical simulation (a) $t = 0$ ms, (b) $t = 1$ ms, (c) $t = 2$ ms, (d) $t = 5$ ms, (e) $t = 15$ ms, (f) $t = 30$ ms	208
Figure 5.15	Bench blast numerical simulation sectional view of rock fragmentation	209
Figure 5.16	Detection of rock fragment in bench blast numerical simulation	209
Figure 5.17	Comparison of numerical model, fieldwork results and Kuz-Ram prediction	211
Figure 5.18	Spacing to burden ratio vs uniformity index	213
Figure 5.19	Spacing to burden ratio vs mean particle size	213
Figure 5.20	A sectional view of rock fragmentation with different S/B ratio	214

Figure 5.21	Rock fragmentation of 1.44 S/B ratio with different time steps	215
Figure 5.22	Rock fragmentation of 1.16 S/B ratio with different time steps	215
Figure 5.23	A sectional view of rock fragmentation with different T/B ratio	217
Figure 5.24	Rock fragmentation of 1.09 T/B ratio with different time steps	218
Figure 5.25	Rock fragmentation of 1.36 T/B ratio with different time steps	218
Figure 5.26	Comparison of rock fragment distribution with different T/B ratio	219
Figure 5.27	Stemming to burden ratio vs mean particle size	220
Figure 5.28	Stemming to burden ratio vs 80% passing size	220
Figure 5.29	A sectional view of rock fragmentation with different B/D ratio	221
Figure 5.30	Rock fragmentation of 40.13 B/D ratio with different time steps	222
Figure 5.31	Rock fragmentation of 26.52 B/D ratio with different time steps	222
Figure 5.32	Burden to hole diameter ratio vs. mean particle size	223
Figure 5.33	Bench height to burden ratio vs mean particle size	224
Figure 5.34	Rock fragmentation of 2.95 BH/B ratio with different time step	225
Figure 5.35	Rock fragmentation of 4.85 BH/B ratio with different time step	225
Figure 5.36	Powder factor vs mean particle size	227
Figure 5.37	Rock fragmentation of 1.8 powder factor with different time step	227
Figure 5.38	Rock fragmentation of 0.25 powder factor with different time step	228
Figure 6.1	RapidMiner Model 1 of Random Forest tree model	233
Figure 6.2	Predicted vs true response of Set 1 to predict d_{50} (a) MATLAB, (b) RapidMiner	236
Figure 6.3	Important parameters for prediction of Set 1 to predict d_{50}	237

Figure 6.4	Predicted vs true response of Set 2 d_{50} (a) MATLAB, (b) RapidMiner	238
Figure 6.5	Important parameters for prediction of Set 2 d_{50}	239
Figure 6.6	Predicted vs true response of Set 1 d_{80} (a) MATLAB, (b) RapidMiner	240
Figure 6.7	Important parameters for prediction of Set 1 d_{80}	241
Figure 6.8	Predicted vs true response of Set 2 d_{80} (a) MATLAB, (b) RapidMiner	242
Figure 6.9	Important parameters for prediction of Set 2 d_{80}	243
Figure 6.10	Predicted vs true response of Set 1 uniformity index (a) MATLAB, (b) RapidMiner	244
Figure 6.11	Important parameters for prediction of Set 1 uniformity index	245
Figure 6.12	Predicted vs true response of Set 2 uniformity index (a) MATLAB, (b) RapidMiner	246
Figure 6.13	Important parameters for prediction of Set 2 uniformity index	247
Figure 6.14	R-squared comparison for prediction of mean particle size	248
Figure 6.15	RMSE comparison for prediction of mean particle size	249
Figure 6.16	R-squared comparison for prediction of d_{80}	250
Figure 6.17	RMSE comparison for prediction of d_{80}	251
Figure 6.18	R-squared comparison for prediction of uniformity index	252
Figure 6.19	RMSE comparison for prediction of uniformity index	252
Figure 7.1	Quarry blast evaluation system for rock fragmentation	262

LIST OF ABBREVIATIONS

ANFO	-	Ammonium Nitrate Fuel Oil
ANN	-	Artificial Neural Networks
AOp		Air-Overpressure
B/D	-	Burden to Hole Diameter ratio
BH/B	-	Bench Height to Burden ratio
BI	-	Blastability Index
BPM	-	Bonded Particle Model
BQS	-	Blastability Quality System
CPM		Corpuscular Particle Method
CRP	-	Close Range Photogrammetry
DEM	-	Discrete Element Method
DOSH	-	Department of Occupational Safety and Health
DSLR		Digital Single-Lens Reflex
EDM		Electronic Distance Measurement
FEM	-	Finite Element Method
FIS	-	Fuzzy Inference System
GCP	-	Ground Control Points
GGSB	-	Gemencheh Granite Sdn Bhd
GPS		Global Positioning System
GSI	-	Geological Strength Index
H		Hardness in Mho Scale
ISRM	-	International Society for Rock Mechanics
JCS	-	Joint Compressive Strength
JPO		Joint plan orientation
JPS		Joint plan spacing
JRC	-	Joint Roughness Coefficient
KMT		Kinetic Molecular Theory
LiDAR		Light Detection and Ranging
LVDT	-	Linear Variable Displacement Transducer
MC		Monte Carlo

MR		Multiple Regression
MVRA	-	Multivariate Regression Analysis
PBM	-	Particle Blast Method
PF	-	Powder Factor
PPV	-	Peak Particle Velocity
RES	-	Rock engineering system
RMD		Rock mass description
RMR	-	Rock Mass Rating
RMS		Root Mean Square
RMSE	-	Root Mean Square Error
RQD	-	Rock Quality Designation
RSR	-	Rock Structure Rating
RTK	-	Real-Time Kinematic
S/B	-	Spacing to Burden ratio
SGI		Specific Gravity Influence
SVM	-	Support Vector Machines
T/B	-	Stemming to Burden ratio
TLS	-	Terrestrial Laser Scanning
UAV	-	Unmanned Aerial Vehicle
UCS	-	Unconfined Compressive Strength
UCT	-	Unconfined Compression Test
USBM		United States Bureau of Mines
UTM	-	Universiti Teknologi Malaysia
VOD	-	Velocity of Detonation

LIST OF SYMBOLS

d_{50}	-	Mean Particle Size
d_{80}	-	Sieve Size at 80% Material Passing
n	-	Uniformity Index
A	-	Rock factor
B	-	Burden
S	-	Spacing
T	-	Stemming
BH	-	Bench Height
D	-	Hole Diameter
d	-	Diameter
Q	-	Mass of explosive in hole
L	-	Charge length
ρ_d	-	dry density
M_s	-	grain weight
V	-	bulk volume
M_{sat}	-	Saturated-surface dry mass
M_{sub}	-	Saturated-submerged mass
ρ_w	-	water density
V_p	-	velocity of longitudinal wave
t_p	-	transit time
D_e	-	equivalent core diameter
P	-	Load
I_s	-	point load strength
σ_t	-	tensile strength
t	-	thickness of rock sample
σ	-	Compressive strength
L_n	-	Normal load
σ_n	-	Normal stress
P_n	-	Pressure to be set on gauge
τ_p	-	Shear stress

c	-	Cohesion
ϕ	-	friction angle
ϕ_r	-	residual friction angle
r	-	Schmidt rebound number wet and weathered fracture surfaces
R	-	Schmidt rebound number on dry unweathered sawn surfaces
J_V	-	Volumetric joint count
ϵ_r	-	Radial (lateral) strain
ϵ_a	-	Axial (vertical) strain
a	-	$\frac{1}{2}$ length of ellipse
b	-	$\frac{1}{2}$ width of ellipse
u	-	Horizontal displacement
k_s	-	Parallel-bond shear stiffness
k_n	-	Parallel-bond normal stiffness

LIST OF APPENDICES

APPENDIX	TITLE	PAGE
Appendix A	Fieldwork	283
Appendix B	Laboratory test results	284

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Blasting has been widely used for rock breakage especially in mining and civil engineering applications because it is more economical (Singh, 2012). In mining and quarrying operations, blasting aim is to extract the largest possible quantity of rock at a minimum cost in a safer manner with minimum side effects. Blasting operation is carried out to provide quality and quantity requirements of production. Assessment of each blast is necessary to ensure the aim of the blast is achieved. The blast design plays an important role in the blast results. A poorly conducted blast will be resulting in poor fragmentation and other blast results such as ground vibration, flyrock, airblast, backbreak and toe formation. These blast results need to be well understood because it is related to health and safety issues.

One of the major concerns related to blasting operation in mining and civil engineering projects is rock fragmentation. In large-scale quarrying activities, rock fragmentation plays a major role due to its direct effects on the costs of drilling, blasting and the efficiency of all the subsystems such as loading, hauling and crushing in mining operations (Dershowitz, 1993; Goodman and Shi, 1985; Faramarzi *et al.*, 2013). Rock fragmentation depends on two groups of variables which are uncontrollable rock mass properties, and parameters of drill and blast design that can be controlled and optimized. The optimisation of blast design parameters to ensure target fragmentation will reduce downstream operation costs (Singh *et al.*, 2016). The optimum blasting pattern for efficiently and economically excavating a quarry can be determined based on the minimum cost of production, which is generally estimated according to the characteristics of rock fragmentation namely mean particle size (d_{50}), uniformity index (n), and sieve size at 80% material passing (d_{80}).

Accurate information about the blast geometry of a quarry rock face will profoundly affect the success of blasting operations. Thus, terrestrial and aerial survey technology can be used to accelerate and to obtain more accurate discontinuity survey. Hämmerle *et al.* (2015) mentioned that it is important for quarry operators to identify the detailed and quickly available geodata of quarries such as breaklines or dump volumes because it is needed for planning and monitoring raw material extraction, calculating extraction costs, and commercial purposes.

Perak Department of Occupational Safety and Health (DOSH) mentioned that most of the quarries inspected by DOSH are rated poor and not a single quarry received a good rating in all of last year. Poor ratings represent a weak security system for the employee's safety aspect and some of the quarry without security system (www.nst.com.my, 2018; www.malaymail.com, 2018). Among the issues of the low ranked is lack of safety features, no housekeeping, no barriers to machineries and untrained personnel handling heavy machineries and blasting. Thus, the numerical simulation and machine learning prediction model developed in this research will help the quarry owners and operators to increase the productivity of the quarry production, preventing accidents and work-related illnesses.

1.2 Problem Statement

Few cases of incident involving rock blasting have been reported in Malaysia, where a few factory workers have been killed or injured after being hit by rock debris from blasting at a nearby quarry, which also damaged cars and buildings along the road (Mohamad *et al.*, 2013; www.thestar.com.my, 2008; www.malaymail.com, 2019; www.thestar.com.my, 2019). Mohamad *et al.* (2013) investigated one of the cases that occurred in Johor, Malaysia which causes many buildings damaged plant and equipment, workers were injured and vehicles were badly damaged and the prices of a loss can reach up to millions of dollars. Their concluded that there are several causes for the incident. First, the people responsible for handling explosives need to be well trained. This is because it will endanger not only quarry workers but

also people's surroundings. Second, the geological conditions which are the uncontrollable parameters should be clearly identified and understood before blast operation. Adhikari and Gupta (1989) also mentioned that properties of rock mass are important parameters that need to be considered in blast design and it is fundamental to understand the effect of discontinuities in rock mass and physicommechanical properties on blasting. Poor blast design geometry also results in poor fragmentation and other blast results. In some cases, trial and error blasting is conducted to improve the blast design because of the limited data of trial and difficulties in getting variability in the blast design. Thus, prediction blasting models need to be extensively studied to produce a more robust and better prediction of rock fragmentation and fracture in quarry blasting.

Several attempts of empirical models have been developed to improve the blast design and prediction of blast results such as rock fragmentation, flyrock, airblast, and ground vibration. However, empirical methods have limited inputs and are unable to predict multiple outputs. With the aid of computer technology, some researchers have developed models using numerical methods to overcome the shortcomings of the empirical methods of fragmentation prediction. Numerical simulation used in this study to evaluate the mechanism of the rock fragmentation related to the geometrical of the open pit and also its rock mass condition. This study also evaluates the behaviour of rock fragmentation blast induced by performing a series of parametric study using numerical simulation. Prediction of rock fragmentation characteristics using machine learning algorithm with different learning's is used to improve the existing predictors and to resolve the blasting challenges. In addition, the parameters that affect blasting need to be identified clearly to get better blast results prediction especially on rock fragmentation.

1.3 Objectives of Study

Hence, in order to address the above problem statements, three main objectives are identified in order to establish a blast evaluation system for better prediction of rock fragmentation characteristics in quarry operation.

1. To determine rock mass classification scoring and blastability index by discontinuity mapping based on the point cloud data from terrestrial and aerial survey technology.

The rock mass is classified using Rock Mass Rating (RMR) and Geological Strength Index (GSI) based on point cloud data obtained from terrestrial and aerial survey technology namely Terrestrial Laser Scanning (TLS) and Unmanned Aerial Vehicle (UAV) respectively. Then, Blastability Index (BI) is determined from RMR and GSI.

2. To evaluate the behaviour of rock fragmentation blast induced by performing a series of parametric study based on the selected parameters through numerical analysis.

The blast design parameters involved are burden, spacing, stemming, hole diameter, bench height and powder factor.

3. To develop new rock fragmentation model through machine learning algorithms for prediction of rock fragmentation characteristics.

The predicted rock fragmentation characteristics are mean particle size (d_{50}), uniformity index (n), and sieve size at 80% material passing (d_{80}).

1.4 Scope of Study

This study presents an assessment of rock fragmentation in quarry blasting at Gemencheh, Negeri Sembilan, Malaysia. The quarry is selected due to safety reason as the bench height is suitable for research purposes. For safety purposes, the newly blast rock surface at quarry is not safe for conventional method. Terrestrial and aerial survey technology namely Terrestrial Laser Scanning (TLS) and Unmanned Aerial Vehicle (UAV) was used for safer fieldwork. The study will focus on the granitic rock quarry operation. The rock properties of intact rock is obtained from laboratory test which are Density test, Ultrasonic velocity test, Point load test, Rebound Hammer Test, Brazilian test, Unconfined compression test, Triaxial compression test and Direct shear test. Based on the rock mass discontinuities obtained from discontinuity mapping and intact rock properties from laboratory test, the rock mass are classified using Rock Mass Rating (RMR) and Geological Strength Index (GSI). From here, the Blastability Index (BI) is identified based on RMR and GSI scoring. The blast result is focused on rock fragmentation; specifically the characteristics of rock fragmentation namely mean particle size (d_{50}), uniformity index (n), and sieve size at 80% material passing (d_{80}). A series of parametric study on rock fragmentation will be made through numerical analysis using Discrete Element Method (DEM) numerical simulation using Bonded Particle Method (BPM) and Particle Blast Method (PBM) to predict the blasting performance. The parameters involved are burden, spacing, stemming, hole diameter, bench height and powder factor. A prediction model of rock fragmentation will be established based on machine learning algorithm with different learning's using MATLAB and RapidMiner software. Linear Regression, Decision Tree, Random Forest and SVM are learnings utilised in this study. Machine Learning algorithm is used to predict the d_{50} , d_{80} and uniformity index as the output product. The best prediction model is selected based on the performance indices which show the highest R-squared value, with the lowest Root Mean Square Error (RMSE) value. The outcome of this study is specifically addressing certain conditions as specified in the scope. The blast evaluation system and prediction for rock fragmentation developed is focused on open pit quarry but this also may be applicable to rock slope.

1.5 Significance of Study

The quarry blast evaluation system and prediction blast model to be developed can improved the existing prediction of rock fragmentation used in quarry operation. Predicting the optimum fragmentation size will allow the quarry owners to select the blast design parameters to produce the material size required at a known cost, as well as select crushers and conveyor systems. The optimum rock fragmentation size can be obtained when the contractor is able to adapt the blasting by knowing the size distribution for specific blast and rock mass conditions. Relationship between the blast parameters involved and the predicted rock fragmentation characteristics will be very beneficial for policymakers, shot-firers and designers associated with quarry blasting for a safe quarry blasting operation. It may deliver engineering justification that may help engineer to make important decisions during the planning, design and production stages of a quarry. The blast evaluation system can produce good fragmentation for the quarry. The good fragmentation may avoid the flyrock incident, thus indirectly will avoid the fatality and bad effect to the surrounding area.

1.6 Thesis outline

This thesis consists of five chapters. The introduction of the research topic in Chapter 1 describes the importance of quarry blast design to the blast results. In this chapter, the problem statement, aim and objectives, scope and significant of the study were all highlighted.

Chapter 2 provides an extensive review of previous literature on the quarry blast model for rock fragmentation and deals exclusively with the theoretical background on the research topic, concepts and applicable methods employed in this research. It highlights the blast mechanism; parameters influence blast results, rock mass classification, blastability index, field data acquisition methods, blast results, methods to predict rock fragmentation, numerical modelling and machine learning.

Chapter 3 explicates the research methodology adopted in this study, discussing the fieldwork and laboratory testing of rock, numerical modelling and parametric study to predict rock fragmentation and finally, prediction using machine learning algorithm.

Chapter 4 presents and discusses the results of fieldwork discontinuity mapping using terrestrial and aerial survey technology, and laboratory work. Based on the data obtained from fieldwork and laboratory work, the rock mass is classified using rock mass classification. Then, blastability index is obtained.

Chapter 5 presents and discusses the results of the behaviour of rock fragmentation induced by blasting based on the selected parameters by performing a series of parametric study using numerical modelling. The rock properties obtained from laboratory tests is utilised in the numerical modelling. The rock fragmentation characteristics is obtained from the numerical modelling and the data used for prediction in Chapter 6.

In Chapter 6, the results of machine learning algorithm prediction to predict rock fragmentation characteristics are presented and discussed in this chapter. The data used in machine learning is based on fieldwork and numerical results.

Chapter 7 covers the research outcomes, and the contribution of knowledge achieved from this study and recommendations for further researches on the subject are presented.

REFERENCES

- Abd Rahman, N., Mansor, M. A., & Ismail, A. R. (2015). Accidents in Mining and Quarry Sites: Rate of Occurrences and Causes. *International Journal of Creative Futures and Heritage*, 3(2), 23–32.
- Abdulhussein, J. H. (2017). Detection and localisation of structural deformations using terrestrial laser scanning and generalised procrustes analysis . *Nottingham Geospatial Institute*, (January).
- Abellán, A., Oppikofer, T., Jaboyedoff, M., Rosser, N. J., Lim, M., & Lato, M. J. (2014a). Review Of Terrestrial Laser Scanning Of Rock Slope Instabilities.
- Abellán, A., Oppikofer, T., Jaboyedoff, M., Rosser, N. J., Lim, M., & Lato, M. J. (2014b). Terrestrial laser scanning of rock slope instabilities. *Earth Surface Processes and Landforms*, 39(1), 80–97.
- Abu Bakar, M. Z., Tariq, S. M., Hayat, M. B., Zahoor, M. K., & Khan, M. U. (2013). Influence of Geological Discontinuities upon Fragmentation by Blasting. *Pakistan Journal of Science*, 65(3).
- Adebola, J. M., & O, P. E. (2016). Rock Fragmentation Prediction using Kuz-Ram Model, 6(5), 110–115.
- Adhikari, G. R., & Gupta, R. N. (1989). Influence of discontinuity structure on rock fragmentation by blasting. *International Journal of Mining and Geological Engineering*, 7(3), 239–248.
- Al-Maamori, H. M. S., El Naggar, M. H., & Micic, S. (2014). A Compilation of the Geo-Mechanical Properties of Rocks in Southern Ontario and the Neighbouring Regions. *Open Journal of Geology*, 04(05), 210–227.
- Amiri, A. (2017). *Investigation of Discrete Element and Bonded Particle Methods for Modelling Rock Mechanics Subjected to Standard Tests and Drilling*. M.Sc Thesis, Politecnico di Milano, Milan, Italy.
- Ampatzi, G., Chatzigogos, N., Makedon, M., Papathanassiou, G., & Marinos, V. (2016). Application of Terrestrial Laser Scanning (Lidar) In Rock Slope Stability. An Example from Northern Greece. *Bulletin of the Geological Society of Greece*, L(May), 586–595.
- Armaghani, D. J., Mahdiyar, A., Hasanipanah, M., Faradonbeh, R. S., Khandelwal,

- M., & Amnieh, H. B. (2016). Risk Assessment and Prediction of Flyrock Distance by Combined Multiple Regression Analysis and Monte Carlo Simulation of Quarry Blasting. *Rock Mechanics and Rock Engineering*, *49*(9), 3631–3641.
- Asl, P. F., Monjezi, M., Hamidi, J. K., & Armaghani, D. J. (2018). Optimization of flyrock and rock fragmentation in the Tajareh limestone mine using metaheuristics method of firefly algorithm. *Engineering with Computers*, *34*(2), 241–251.
- Assali, P., Grussenmeyer, P., Villemin, T., Pollet, N., & Viguiier, F. (2014). Surveying and modeling of rock discontinuities by terrestrial laser scanning and photogrammetry: Semi-automatic approaches for linear outcrop inspection. *Journal of Structural Geology*, *66*, 102–114. Retrieved from <http://dx.doi.org/10.1016/j.jsg.2014.05.014>
- Babaeian, M., Ataei, M., Sereshki, F., Sotoudeh, F., & Mohammadi, S. (2019). A new framework for evaluation of rock fragmentation in open pit mines. *Journal of Rock Mechanics and Geotechnical Engineering*, *11*(2), 325–336.
- Badroddin, M., Bakhtavar, E., Khoshrou, H., & Rezaei, B. (2012). Efficiency of standardized image processing in the fragmentation prediction in the case of Sungun open-pit mine. *Arabian Journal of Geosciences*, *6*(9), 3319–3329.
- Bahrani, A., Monjezi, M., Goshtasbi, K., & Ghazvinian, A. (2010). Prediction of rock fragmentation due to blasting using artificial neural network. *Engineering with Computers*, *27*(2), 177–181.
- Bahrani, N., Kaiser, P. K., & Valley, B. (2014). Distinct element method simulation of an analogue for a highly interlocked, non-persistently jointed rockmass. *International Journal of Rock Mechanics and Mining Sciences*, *71*, 117–130.
- Bajpayee, T. S., Rehak, T. R., Mowrey, G. L., & Ingram, D. K. (2004). Blasting injuries in surface mining with emphasis on flyrock and blast area security. *Journal of Safety Research*, *35*(1), 47–57.
- Bakhtavar, E., Khoshrou, H., & Badroddin, M. (2014). Using dimensional-regression analysis to predict the mean particle size of fragmentation by blasting at the Sungun copper mine. *Arabian Journal of Geosciences*, *8*(4), 2111–2120.
- Bamford, T., Esmaceli, K., & Schoellig, A. P. (2017). A real-time analysis of rock fragmentation using UAV technology. *International Journal of Mining Reclamation and Environment*, *31*(6), 439–456.

- Barton, N. . (1973). Review of a new shear strength criterion for rock joints. *Eng. Geol.*, 7, 287–332.
- Basu, A., Mishra, D. A., & Roychowdhury, K. (2013). Rock failure modes under uniaxial compression, Brazilian, and point load tests. *Bulletin of Engineering Geology and the Environment*, 72(3–4), 457–475.
- Bhandari S. (1997). *Engineering Rock Blasting Operations*. Boca Raton: Taylor & Francis.
- Bieniawski, Z. T. (1989). *Engineering-Rock-Mass-Classifications*. John Wiley & Sons Inc.
- Bobet, A., Fakhimi, A., Johnson, S., Morris, J., Tonon, F., & Yeung, M. R. (2009). Numerical Models in Discontinuous Media: Review of Advances for Rock Mechanics Applications. *Journal of Geotechnical and Geoenvironmental Engineering*, 135(11), 1547–1561.
- Bohler, W., & Marbs, A. (2004). 3D scanning and photogrammetry for heritage recording: a comparison. In *Proceedings of the 12th International Conference on Geoinformatics* (pp. 291–298). Citeseer.
- Boikov, A. V., Savelev, R. V., & Payor, V. A. (2018). DEM Calibration Approach: Design of experiment. *Journal of Physics: Conference Series*, 1015(3).
- Bond, C. E., Cawood, A. J., Bond, C. E., Howell, J. A., Butler, R. W. H., & Totake, Y. (2017). LiDAR , UAV or compass-clinometer ? Accuracy , coverage and the effects on structural models LiDAR , UAV or compass-clinometer ? Accuracy , coverage and the effects on structural models. *Journal of Structural Geology*, 98(April), 67–82. Retrieved from <http://dx.doi.org/10.1016/j.jsg.2017.04.004>
- Burkov, A. (2019). The Hundred-Page Machine Learning Book-Andriy Burkov. *Expert Systems*, 5(2), 132–150.
- Carvajal-Ramírez, F., Agüera-Vega, F., & Martínez-Carricondo, P. J. (2016). Effects of image orientation and ground control points distribution on unmanned aerial vehicle photogrammetry projects on a road cut slope. *Journal of Applied Remote Sensing*, 10(3), 034004.
- Cevizci, H., & Ozkahraman, H. T. (2012). The effect of blast hole stemming length to rockpile fragmentation at limestone quarries. *International Journal of Rock Mechanics and Mining Sciences*, 53, 32–35.
- Cevizci, Halim. (2013). New approach on blasting for excavation, 5(1), 104–111.
- Chakraborty, A. K., Raina, A. K., Ramulu, M., Choudhury, P. B., Haldar, A., Sahu,

- P., & Bandopadhyay, C. (2004). Parametric study to develop guidelines for blast fragmentation improvement in jointed and massive formations. *Engineering Geology*, 73(1–2), 105–116.
- Chatziangelou, M., & Christaras, B. (2015). A geological classification of rock mass quality and blast ability for intermediate spaced formations. *International Journal of Engineering and Innovative Technology*, 4(9), 52–61.
- Chatziangelou, M., & Christaras, B. (2016). A Geological Classification of Rock Mass Quality and Blast Ability for Widely Spaced Formations. *Journal of Geological Resource and Engineering*, 4, 160–174.
- Chatziangelou, Maria, & Christaras, B. (2017). A New Development of BQS (Blastability Quality System) for Closely Spaced Formations. *Journal of Geological Resource and Engineering*, 1, 24–37.
- Chekole, S. D. (2014). Surveying with GPS , total station and terrestrial laser scanner: a comparative study. *MSc Thesis: School of Architecture and the Built Environment, Royal Institute of Technology (KTH)*, (3131), 1–55.
- Cho, S. H., Nishi, M., Yamamoto, M., & Kaneko, K. (2003). Fragment Size Distribution in Blasting. *Materials Transactions*, 44(5), 951–956.
- Christaras, B., & Chatziangelou, M. (2014). Blastability Quality System (BQS) for using it, in bedrock excavation. *Structural Engineering and Mechanics*, 51(5), 823–845.
- Chung, S. H., & Katsabanis, P. D. (2000). Fragmentation prediction using improved engineering formula. *FRAGABLAST – Int. J. Blast. Fragment.* 4, 198–207.
- Cooper, M. A. R. and Robson, S. (1990). High Precision Photogrammetric Monitoring of the Deformation of a Steel Bridge. *The Photogrammetric Record*, 13(76), 505–510.
- Cundall, P. A., & Strack, O. D. L. (1979). A discrete numerical model for granular assemblies. *Géotechnique*, 29(1), 47–65.
- Cundall, P., Ruest, M., Chitombo, G., Esen, S., & Cunningham, C. (2001). *The Hybrid Stress Blasting Model: A Feasibility Study*. Confidential report. JKMRC, ITASCA and AEL.
- Cunningham. (1983). The Kuz–Ram model for prediction of fragmentation from blasting. In *In: Proceedings of the 1st international symposium on rock fragmentation by blasting. Lulea, Sweden* (pp. 439–53.).
- Cunningham, C. V. B. (1987). Fragmentation estimations and the Kuz-Ram model—

- four years on. In *Proc. 2nd Int. Symp. on Rock Fragmentation by Blasting, Keystone, Colorado, USA, 23–26 August* (pp. 475–487).
- Cunningham, C. V. B. (2005). The Kuz-Ram fragmentation model – 20 years on. In *Brighton Conference Proceedings 2005*.
- D.Priest, S. (1994). The collection and analysis of discontinuity orientation data for engineering design, with examples. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics*, 31(4), 199.
- Dai, Y., Ma, F., Zhu, X., Liu, H., Huang, Z., & Xie, Y. (2019). Mechanical tests and numerical simulations for mining seafloor massive sulfides. *Journal of Marine Science and Engineering*, 7(8).
- Dawes, J. J. (1986). *The study of blast performance and design in mining via the analysis of ground vibrations. PhD. Thesis, University of Queensland, Australia.*
- Deere, D. U., & Miller, R. P. (1966). *Engineering classification and index properties of rock. Technical Report No. AFNL-TR-65-116. Albuquerque, NM: Air Force Weapons Laboratory.*
- Dehghani, H., Babanouri, N., Alimohammadnia, F., & Kalhori, M. (2020). Blast-Induced Rock Fragmentation in Wet Holes. *Mining, Metallurgy and Exploration*.
- Department Of Occupational Safety And Health (DOSH). (2007). *Guidelines for Public Safety and Health At Construction Sites.*
- Dershowitz, W. S. (1993). Geometric conceptual models for fractured rock masses: implications for groundwater flow and rock deformation. In *ISRM International Symposium - EUROCK 93, 21-24 June, Lisboa, Portugal* (pp. 71–81). International Society for Rock Mechanics and Rock Engineering.
- Dey, K., & Sen, P. (2003). Concept of blastability – An update. *The Indian Mining & Engineering Journal*, 42(8 & 9), 24–31.
- Dong, S., Wang, Y., & Xia, Y. (2006). A finite element analysis for using Brazilian disk in split Hopkinson pressure bar to investigate dynamic fracture behavior of brittle polymer materials. *Polymer Testing*, 25(7), 943–952.
- DOSH. (n.d.). <https://www.dosh.gov.my/index.php/component/content/article/352-osh-info/accident-case/955-accident-case>.
- Duan, G., Li, J., Zhang, J., Assefa, E., & Sun, X. (2019). Mechanical Properties and Failure Modes of Rock Specimens with Specific Joint Geometries in Triaxial

- Unloading Compressive Test. *Advances in Materials Science and Engineering*, 2019.
- DYNONOBEL. (2010). Blasting and Explosives Quick Reference Guide. In *Dyno Nobel Asia Pacific Pty Limited, Kalgoorlie* (p. 32pp).
- Ebrahimi, E., Monjezi, M., Khalesi, M. R., & Armaghani, D. J. (2015). Prediction and optimization of back-break and rock fragmentation using an artificial neural network and a bee colony algorithm. *Bulletin of Engineering Geology and the Environment*, 75(1), 27–36.
- Eisenbeiss, H. (2009). *UAV photogrammetry*.
- El-Ashmawy, K. L. A. (2015). A comparison between analytical aerial photogrammetry, laser scanning, total station and global positioning system surveys for generation of digital terrain model. *Geocarto International*, 30(2), 154–162.
- Enayatollahi, I., Aghajani Bazzazi, A., & Asadi, A. (2013). Comparison Between Neural Networks and Multiple Regression Analysis to Predict Rock Fragmentation in Open-Pit Mines. *Rock Mechanics and Rock Engineering*, 47(2), 799–807.
- Engin. (2009). A practical method of bench blasting design for desired fragmentation based on digital image processing technique and Kuz–Ram model..pdf. In *In: Proceedings of the 9th international symposium on rock fragmentation by blasting. Granada, Spain* (pp. 257–63.).
- Engin. (2016). A practical method of bench blasting design for desired fragmentation based on digital image processing technique and Kuz-Ram model, (August).
- Esmaeili, M., Salimi, A., Drebenstedt, C., Abbaszadeh, M., & Aghajani Bazzazi, A. (2014). Application of PCA, SVR, and ANFIS for modeling of rock fragmentation. *Arabian Journal of Geosciences*, 8(9), 6881–6893.
- Fakhimi, A., & Villegas, T. (2007). Application of dimensional analysis in calibration of a discrete element model for rock deformation and fracture. *Rock Mechanics and Rock Engineering*, 40(2), 193–211.
- Fakunle, A. A. (2016). *Detection of Weathering Signatures using UAV Photogrammetry in Comparison with Ground- Based Sensors*. Msc Thesis, University of Twente.
- Faramarzi, F., Mansouri, H., & Ebrahimi Farsangi, M. a. (2013). A rock engineering systems based model to predict rock fragmentation by blasting. *International*

- Journal of Rock Mechanics and Mining Sciences*, 60, 82–94.
- Ferrero, A. M., Forlani, G., Roncella, R., & Voyat, H. I. (2009). Advanced geostructural survey methods applied to rock mass characterization. *Rock Mechanics and Rock Engineering*, 42(4), 631–665.
- Flores-Johnson, E. A., Wang, S., Maggi, F., El Zein, A., Gan, Y., Nguyen, G. D., & Shen, L. (2016). Discrete element simulation of dynamic behaviour of partially saturated sand. *International Journal of Mechanics and Materials in Design*, 12(4), 495–507.
- Garvey, R. J. (2013). *A study of Unstable Rock Failures Using Finite Difference and Discrete Element Methods*.
- Ghasemi, E., Sari, M., & Ataei, M. (2012). Development of an empirical model for predicting the effects of controllable blasting parameters on flyrock distance in surface mines. *International Journal of Rock Mechanics and Mining Sciences*, 52(December 2016), 163–170.
- Gomes-Sebastiao, G. L., & De Graaf, W. W. (2017). An investigation into the fragmentation of blasted rock at Gomes Sand. *Journal of the Southern African Institute of Mining and Metallurgy*, 117(4), 321–328.
- González-Aguilera, D., Muñoz-Nieto, A., Gómez-Lahoz, J., Herrero-Pascual, J., & Gutierrez-Alonso, G. (2009). 3D digital surveying and modelling of cave geometry: Application to paleolithic rock art. *Sensors*, 9(2), 1108–1127.
- Goodman, R. E., & Shi, G. (1985). *Block theory and its application to rock engineering*. Englewood Cliffs, N.J. : Prentice-Hall.
- Guo, L., Xiang, J., Latham, J. P., & Izzuddin, B. (2016). A numerical investigation of mesh sensitivity for a new three-dimensional fracture model within the combined finite-discrete element method. *Engineering Fracture Mechanics*, 151, 70–91.
- Guta, H. E. (2017). *Use of Unmanned Aerial Vehicles Compared To Terrestrial Laser Scanning For Characterizing Discontinuities on Rock Use of Unmanned Aerial Vehicles Compared to Terrestrial Laser Scanning For Characterizing Exposures*. University of Twente.
- Hagan, T. (1983). The influence of controllable blast parameters on fragmentation and mining costs. In *In: Proceedings of the 1st International Symposium on Rock Fragmentation by Blasting I* (p. 31e2).
- Hajihassani, M., Jahed Armaghani, D., Sohaei, H., Tonnizam Mohamad, E., &

- Marto, A. (2014). Prediction of airblast-overpressure induced by blasting using a hybrid artificial neural network and particle swarm optimization. *Applied Acoustics*, 80, 57–67.
- Hämmerle, M., Schütt, F., & Höfle, B. (2015). Terrestrial and UAS-borne Imagery for Quarry Monitoring with Low-Cost Structure from Motion, 2–3.
- Hasanipanah, M., Monjezi, M., Shahnazar, A., Jahed Armaghani, D., & Farazmand, A. (2015). Feasibility of indirect determination of blast induced ground vibration based on support vector machine. *Measurement*, 75, 289–297.
- Hellmy, M. A. A., Muhammad, R. F., Shuib, M. K., Fatt, N. T., Abdullah, W. H., Bakar, A. A., & Kugler, R. (2019). Rock slope stability analysis based on terrestrial LiDAR on karst hills in kinta valley geopark, perak, peninsular Malaysia. *Sains Malaysiana*, 48(11), 2595–2604.
- Hettinger, M. R. (2015). The Effects of Short Delay Times on Rock Fragmentation in Bench Blasts, 1–155.
- Hjelmberg H. (1983). Some ideas on how to improve calculations of the fragment size distribution in bench blasting. In *In: Proceedings of the 1st international symposium on rock fragmentation by blasting. Lulea, Sweden* (pp. 469–94).
- Hoek, E., Kaiser, P. K., & Bawden, W. . (1995). *Support of Underground*. Rotterdam, Balkema.
- Hosseini, M., & Seifi, M. (2014). Assessing the effect of delay blasting on measuring the size distribution of blasted rock at Alvand Qoly limestone mine, (December), 2014.
- Huang, H., Lecampion, B., & Detournay, E. (2013). Discrete element modeling of tool-rock interaction I: Rock cutting. *International Journal for Numerical and Analytical Methods in Geomechanics*, 37(13), 1913–1929.
- Hudaverdi, T., Kuzu, C., & Fisne, A. (2012). Investigation of the blast fragmentation using the mean fragment size and fragmentation index. *International Journal of Rock Mechanics and Mining Sciences*, 56, 136–145.
- Hudson, J. A., & Harrison, J. P. (2000). *Engineering Rock Mechanics : An Introduction to the Principles*. Elsevier Science (1864).
- Hussin, H., Fauzi, N. bt, Jamaluddin, T. A., & Arifin, M. H. (2017). Rock mass quality effected by lineament using rock mass rating (rmr)-case study from former quarry site. *Earth Science Malaysia*, 1(2), 13–16.
- Hutchinson, D., & Diederichs, M. (1996). *Cable bolting in underground mines*.

- Richmond, British Columbia, Canada.: Bitech Publishers, Ltd.
- Ibrahim, D. (2016). An Overview of Soft Computing. *Procedia Computer Science*, 102(August), 34–38.
- Institute of Quarrying Malaysia. (2017). Training Course for Shot-Firers.
- ISRM. (1978). International society for rock mechanics commission on standardization of laboratory and field tests. Suggested methods for the quantitative description of discontinuities in rock masses. *International Journal of Rock Mechanics and Mining Sciences And*, 15(6), 319–368.
- Itasca. (2003). PFC3D PFC2D User's Manual. Itasca Consulting Group Inc., Minneapolis.
- Jang, H., & Topal, E. (2014). A review of soft computing technology applications in several mining problems. *Applied Soft Computing Journal*, 22, 638–651.
- Just, G. D. (1984). Incremental explosive energy distribution in blasting design. *International Journal of Mining Engineering*, 2(2), 107–118.
- Karadogan, A., Kahriman, A., & Ozer, U. (2014). A new damage criteria norm for blast-induced ground vibrations in Turkey. *Arabian Journal of Geosciences*, 7(4), 1617–1626.
- Karajan, N., Han, Z., Teng, H., & Wang, J. (2013). Interaction Possibilities of Bonded and Loose Particles in LS-DYNA. In *9th European LS-DYNA Conference* (pp. 1–27).
- Katterfeld, A., Coetzee, C., Donohue, T., Fottner, J., Grima, A., Ramirez Gomez, A., ... Zegzulka, J. (2019). Calibration of DEM Parameters for Cohesionless Bulk Materials under Rapid Flow Conditions and Low Consolidation, (July).
- Kazerani, T., Yang, Z. Y., & Zhao, J. (2012). A discrete element model for predicting shear strength and degradation of rock joint by using compressive and tensile test data. *Rock Mechanics and Rock Engineering*, 45(5), 695–709.
- Kirby, J. I., Harris, G. H., & Tidman, J. P. (1987). ICI's computer blasting model SABREX – basic principles and capabilities. In *Proc ISEE 13th Ann Conf Expl & Blasting Techn* (pp. 184-194. ISEE, Cleveland OH.).
- Kleine, T. (1988). *A mathematical model of rock breakage by blasting. PhD Thesis. The University of Queensland, Australia.*
- Knapen, B. V. A. N., & Slob, S. (2006). Identification and characterisation of rock mass discontinuity sets using 3D laser scanning, (438), 1–10.
- Kou, & Rustan. (1993). Computerized design and result prediction of bench blasting.

- In *In: Proceedings of the 4th international symposium on rock fragmentation by blasting. Vienna* (pp. 263–71).
- Kulatilake, P. H. S. W., Hudaverdi, T., & Wu, Q. (2012). New Prediction Models for Mean Particle Size in Rock Blast Fragmentation. *Geotechnical and Geological Engineering*, 30(3), 665–684.
- Kulatilake, P. H. S. W., Qiong, W., Hudaverdi, T., & Kuzu, C. (2010). Mean particle size prediction in rock blast fragmentation using neural networks. *Engineering Geology*, 114(3–4), 298–311.
- Kwong, A. K. L., Kwok, H., Wong, A., Sar, H. K., Kwong, A. K. L., Kwok, H., ... Sar, H. K. (2007). Use of 3D Laser Scanner for Rock Fractures Mapping Use of 3D Laser Scanner for Rock Fractures Mapping, (May 2007), 13–17.
- Langefors, U., & Kihlstrom, B. (1963). *The modern technique of rock blasting*. New York: Wiley;
- Larsson, B. (1974). Report on blasting of high and low benches - fragmentation from production blasts. In *Proc Discussion meeting BK 74, Swedish Rock Construction Committee, Stockholm* (pp. 247–273).
- Lerma, J. L., Navarro, S., Cabrelles, M., & Villaverde, V. (2010). Terrestrial laser scanning and close range photogrammetry for 3D archaeological documentation: the Upper Palaeolithic Cave of Parpalló as a case study. *Journal of Archaeological Science*, 37(3), 499–507. Retrieved from <http://dx.doi.org/10.1016/j.jas.2009.10.011>
- Lilly, P. (1986). An empirical method of assessing rockmass blastability. In *In: Proceedings of the Large Open Pit Planning Conference, Parkville, Victoria, Australian IMM* (pp. 89–92).
- Lisjak, A., & Grasselli, G. (2014). A review of discrete modeling techniques for fracturing processes in discontinuous rock masses. *Journal of Rock Mechanics and Geotechnical Engineering*, 6(4), 301–314. Retrieved from <http://dx.doi.org/10.1016/j.jrmge.2013.12.007>
- Livermore Software Technology Corporation (LSTC). (2012). LS-DYNA keyword user manual version 971, I(August).
- Luhmann, T., Robson, S., Kyle, S., & Harley, I. (2006). *Close Range Photogrammetry. Collision. The International Compendium for Crash Research* (Vol. 2).
- Lundborg, N., Persson, A., Ladegaard-Pedersen, A., & Holmberg, R. (1975).

- Keeping the lid on flyrock in open-pit blasting. *Eng Min J*; 176, 95–100.
- Ma, Y. (2017). Discrete element modeling of the brittle-ductile transition in strength tests for quasi-brittle materials, (May), 240.
- Maar, H., & Zogg, H.-M. (2014). WFD – Wave Form Digitizer Technology White Paper, 1–12.
- Mackenzie, A. . (1966). Cost of explosives—do you evaluate it properly? *Mining Congress Journal*, 52(5), 32–41.
- Mahabadi, O. K., Cottrell, B. E., & Grasselli, G. (2010). An example of realistic modelling of rock dynamics problems: FEM/DEM simulation of dynamic brazilian test on Barre Granite. *Rock Mechanics and Rock Engineering*, 43(6), 707–716.
- Mardalizad, A., Manes, A., & Giglio, M. (2016). An investigation in constitutive models for damage simulation of rock material. In *ALIAS – Associazione Italiana Per L'analisi Delle Sollecitazioni*.
- Marinos, P., & Hoek, E. (2000). GSI: A geologically friendly tool for rock mass strength estimation. *Proc. GeoEng2000 Conference*, 1422–1442.
- Marinos, V., Marinos, P., & Hoek, E. (2007). Geological Strength Index (GSI). A characterization tool for assessing engineering properties for rock masses. *Underground Works under Special Conditions*, (July), 13–21. Retrieved from <http://www.crcnetbase.com/doi/10.1201/NOE0415450287.ch2>
- Martínez-Carricondo, P., Agüera-Vega, F., Carvajal-Ramírez, F., Mesas-Carrascosa, F. J., García-Ferrer, A., & Pérez-Porras, F. J. (2018). Assessment of UAV-photogrammetric mapping accuracy based on variation of ground control points. *International Journal of Applied Earth Observation and Geoinformation*, 72(May), 1–10. Retrieved from <https://doi.org/10.1016/j.jag.2018.05.015>
- Martinez-Ramon, M., & Cristodoulou, C. (2006). *Support Vector Machines for Antenna Array Processing and Electromagnetic*. Morgan & Claypool, USA: Universidad Carlos III de Madrid, Spain.
- Mat Zam, P. M., Fuad, N. A., Yusoff, A. R., & Majid, Z. (2018). Evaluating the performance of terrestrial laser scanning for landslide monitoring. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives*, 42(4/W9), 35–55.
- Matsuda, Y., & Iwase, Y. (2002). Numerical simulation of rock fracture using three-dimensional extended discrete element method. *Earth, Planets and Space*,

54(4), 367–378.

- Mehrdanesh, A., Monjezi, M., & Sayadi, A. R. (2018). Evaluation of effect of rock mass properties on fragmentation using robust techniques. *Engineering with Computers*, 34(2), 253–260.
- Mindess, S., J. F. Young, & Darwin., D. (2003). *Concrete*. Prentice Hall.
- Mohamad, E. T., Armaghani, D. J., & Motaghedi, H. (2013). The effect of geological structure and powder factor in flyrock accident, Masai, Johor, Malaysia. *Electronic Journal of Geotechnical Engineering*, 18 X, 5661–5672.
- Mohammadnejad, M., Gholami, R., Ramezanzadeh, A., & Jalali, M. (2011). Prediction of blast-induced vibrations in limestone quarries using Support Vector Machine. *Journal of Vibration and Control*, 18(9), 1322–1329.
- Mohebi, J., Zadeh Shirazi, A., & Tabatabaee, H. (2015). Adaptive-neuro fuzzy inference system (Anfis) model for prediction of blast-induced ground vibration. *Sci Int*, 27(3), 2079–2091.
- Monjezi, M., Bahrami, A., & Yazdian Varjani, A. (2010). Simultaneous prediction of fragmentation and flyrock in blasting operation using artificial neural networks. *International Journal of Rock Mechanics and Mining Sciences*, 47(3), 476–480.
- Monjezi, M., Rezaei, M., & Yazdian Varjani, A. (2009). Prediction of rock fragmentation due to blasting in Gol-E-Gohar iron mine using fuzzy logic. *International Journal of Rock Mechanics and Mining Sciences*, 46(8), 1273–1280.
- Monjezi, Masoud, Mohamadi, H. A., Barati, B., & Khandelwal, M. (2012). Application of soft computing in predicting rock fragmentation to reduce environmental blasting side effects. *Arabian Journal of Geosciences*, 7(2), 505–511.
- Morin, M. a., & Ficarazzo, F. (2006). Monte Carlo simulation as a tool to predict blasting fragmentation based on the Kuz–Ram model. *Computers & Geosciences*, 32(3), 352–359.
- Mueller, J. P., & Massaron, L. (2016). *Machine Learning for dummies*. Hoboken, New Jersey: John Wiley & Sons, Inc.
- Munjiza, A. (2004). *The Combined Finite-Discrete Element Method*. John Wiley & Sons Ltd.
- Murlidhar, B. R., Armaghani, D. J., Mohamad, E. T., & Changthan, S. (2018). Rock Fragmentation Prediction through a New Hybrid Model Based on Imperial

- Competitive Algorithm and Neural Network. *Smart Construction Research*, 2(3), 1–12.
- Nasiman, Zainariah, R., & Ramli., M. F. (1996). Fracture pattern and its relationship to groundwater in hard rocks of Negeri Sembilan. *Warta Geologi, Geological Society of Malaysia Newsletter*, 22(3), 232–233.
- Nikolić, M., Roje-Bonacci, T., & Ibrahimbegović, A. (2016). Pregled numeričkih metoda za modeliranje u mehanici stijena. *Tehnicki Vjesnik*, 23(2), 627–637.
- Norizan, F., Abd Rashid, Mohd Fadhli Roslan, N. L., Sa'ari, R., Ibrahim, Z., Mustaffar, M., & Hezmi, M. A. (2016). Monitoring Laboratory Scale River Channel Profile Changes Using Digital Close Range Photogrammetry Technique. *Malaysian Journal of Civil Engineering*, 28(3), 252–266.
- Nur Lyana, K., Hareyani, Z., Kamar Shah, A., & Mohd. Hazizan, M. H. (2016). Effect of Geological Condition on Degree of Fragmentation in a Simpang Pulai Marble Quarry. *Procedia Chemistry*, 19, 694–701.
- Oñate, E., Zárate, F., Celigueta, M. A., González, J. M., Miquel, J., Carbonell, J. M., ... Santasusana, M. (2018). Advances in the DEM and coupled DEM and FEM techniques in non linear solid mechanics. *Computational Methods in Applied Sciences*.
- Onederra, I. (2004). Breakage and fragmentation modelling for underground production blasting applications. *IRR Drilling & Blasting 2004 Conference*, 1–19.
- Oppikofer, T., Bunkholt, H., Fischer, L., Saintot, a, Hermanns, R., Carrea, D., ... Jaboyedoff, M. (2012). Investigation and monitoring of rock slope instabilities in Norway by terrestrial laser scanning. *Landslides and Engineered Slopes. Protecting Society through Improved Understanding. Proceedings of the 11th International and 2nd North American Symposium on Landslides*, 1235–1241.
- Oraee, K., & Asi, B. (2006). Prediction of Rock Fragmentation in Open Pit Mines, using Neural Network Analysis. *Fifteenth International Symposium on Mine Planning and Equipment Selection (MPES 2006), Turin, Italy.*, (9821), 966–978.
- Palmstrom, A. (1982). The volumetric joint count: a useful and simple measure of the degree of rock mass jointing. *Proc. of the 4th Congr. Int. Assoc. of Engng. Geology*, 2(3), 221–228.
- Panthee, S., Khanal, M., & Singh, T. N. (2016). Geotechnical and geomechanical

- characteristics of the rocks along tunnel of Kulekhani III Hydro-electric Project. *Journal of Nepal Geological Society*, 50(1), 39–50.
- Paswan, R. K., & Jha, R. R. (2012). Rock Fragmentation by Blasting.
- Patton, F. . (1966). Multiple modes of shear failure in rock. In *Proc. 1st Congr. Int. Soc. Rock Mech.* (pp. 509–513).
- Pierce, M., Cundall, P., Potyondy, D., & Ivars, D. (2010). A synthetic rock mass model for jointed rock. *Rock Mechanics: Meeting Society's Challenges and Demands*, (December 2015), 341–349.
- Potyondy, D. O., & Cundall, P. A. (2004). A bonded-particle model for rock. *International Journal of Rock Mechanics and Mining Sciences*, 41(8 SPEC.ISS.), 1329–1364.
- Prasad, S., Choudhary, B. S., & Mishra, A. K. (2017). Effect of Stemming to Burden Ratio and Powder Factor on Blast Induced Rock Fragmentation– A Case Study. *IOP Conference Series: Materials Science and Engineering*, 225, 012191.
- Preston, C. (1995). 3D Blast design for ring blasting in underground mines. In *Proceedings of EXPLOR 95, The Australasian Institute of Mining and Metallurgy*, (pp. 1-12 (Late attachment)). Brisbane, Australia.
- Rajpot, M. A. (2009). *The Effect of Fragmentation Specification on Blasting Cost by*. Queen's University.
- Riquelme, A. J., Abellán, A., & Tomás, R. (2015). Discontinuity spacing analysis in rock masses using 3D point clouds. *Engineering Geology*, 195, 185–195.
- Rojek, J., Oñate, E., Labra, C., & Kargl, H. (2011). Discrete element simulation of rock cutting. *International Journal of Rock Mechanics and Mining Sciences*, 48(6), 996–1010.
- Russhakim, N. A. S., Ariff, M. F. M., Majid, Z., Idris, K. M., Darwin, N., Abbas, M. A., ... Yusoff, A. R. (2019). The Suitability Of Terrestrial Laser Scanning For Building Survey And Mapping Applications. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 42(2/W9), 663–670.
- Rustan, A, & Nie, S. (1987). *Fragmentation model at rock blasting. Research Rpt TULEA 1987:07.Luleå University of Techn, Luleå, Sweden.*
- Rustan, Agne. (1998). *Rock Blasting Terms and Symbols: A Dictionary of Symbols and Terms in Rock Blasting and Related Areas Like Drilling, Mining and Rock Mechanics.*

- Sayadi, A., Monjezi, M., Talebi, N., & Khandelwal, M. (2013). A comparative study on the application of various artificial neural networks to simultaneous prediction of rock fragmentation and backbreak. *Journal of Rock Mechanics and Geotechnical Engineering*, 5(4), 318–324.
- Segaetsho, G., & Zvarivadza, T. (2019). Application of rock mass classification and Blastability Index for the improvement of wall control: A hardrock mining case study. *Journal of the Southern African Institute of Mining and Metallurgy*, 119(1), 31–40.
- Segarra, P., Domingo, J. F., López, L. M., Sanchidrián, J. A., & Ortega, M. F. (2010). Prediction of near field overpressure from quarry blasting. *Applied Acoustics*, 71(12), 1169–1176.
- Sereshki, F., Hoseini, S. M., & Ataei, M. (2016). Blast fragmentation analysis using image processing. *International Journal of Mining and Geo-Engineering Blast Fragmentation Analysis Using Image Processing*, 211–218.
- Shahrin, M. I., Abdullah, R. A., Jeon, S., Jeon, B., Sa'ari, R., & Alel, M. N. A. (2019). Numerical Simulation on the Effect of Stemming to Burden Ratio on Rock Fragmentation by Blasting. In *The 5th ISRM Young Scholars' Symposium on Rock Mechanics (YSRM 2019) & International Symposium on Rock Engineering for Innovative Future (REIF 2019)*.
- Shahrin, M. I., Abdullah, R. A., Sa, R., & Alel, M. N. A. (2019). Effect of Burden to Hole Diameter Ratio on Rock Fragmentation by Blasting using LS-DYNA. In *Rock Dynamics Summit, Okinawa, Japan*.
- Sharma, Abhinav. (2017). *Estimating The Effects Of Blasting Vibrations On The High-Wall Stability*. University of Kentucky.
- Sharma, Abhishek, Mishra, A. K., Choudhary, B. S., & Meena, R. (2019). Impact of blast design parameters on rock fragmentation in building stone quarries. *Current Science*, 116(11), 1861–1867.
- Shi, X. Z., Zhou, J., Wu, B. B., Huang, D., & Wei, W. (2012). Support vector machines approach to mean particle size of rock fragmentation due to bench blasting prediction. *Transactions of Nonferrous Metals Society of China (English Edition)*, 22(2), 432–441.
- Shim, H.-J., Ryu, D.-W., Chung, S.-K., Synn, J.-H., & Song, J.-J. (2009). Optimized blasting design for large-scale quarrying based on a 3-D spatial distribution of rock factor. *International Journal of Rock Mechanics and Mining Sciences*,

46(2), 326–332.

- Siddiqui, F. I., Shah, S. M. A., & Behan, M. Y. (2009). Measurement of Size Distribution of Blasted Rock Using Digital Image Processing. *Engineering Science*, 20(2), 81–93.
- Silva, J., Worsey, T., & Lusk, B. (2019). Practical assessment of rock damage due to blasting. *International Journal of Mining Science and Technology*, 29(3), 379–385. Retrieved from <https://doi.org/10.1016/j.ijmst.2018.11.003>
- Singh, P. K., Roy, M. P., Paswan, R. K., Sarim, M., Kumar, S., & Ranjan Jha, R. (2016). Rock fragmentation control in opencast blasting. *Journal of Rock Mechanics and Geotechnical Engineering*, 8(2), 225–237.
- Singh, S. Paul, & Xavier, P. (2005). Causes, impact and control of overbreak in underground excavations. *Tunnelling and Underground Space Technology*, 20(1), 63–71.
- Singh, S.P., & H, A. (2012). Investigation of blast design parameters to optimize fragmentation. In *Fragblast 10, International conference on fragmentation by blasting*.
- Singh, S.P, & Abdul, H. (2012). Rock fragmentation by blasting : Fragblast 10. In *proceedings of the 10th International Symposium on Rock Fragmentation by Blasting*. New Delhi, India.
- Singh, T. N. (2012). New Trends in Economical and Safe Rock Blasting. *Journal of Powder Metallurgy & Mining*, 01(02).
- Siskind, D. E., Stagg, M. S., Kopp, J. W., & Dowding, C. H. (1980). *Structure Response and Damage Produced By Ground Vibration From Surface Mine Blasting. Report of Investigations - 8507*. [https://doi.org/10.1016/0148-9062\(81\)91353-x](https://doi.org/10.1016/0148-9062(81)91353-x)
- Sjöberg, J., Schill, M., Hilding, D., Yi, C., Nyberg, U., & Johansson, D. (2012). Computer simulations of blasting with precise initiation. *ISRM International Symposium - EUROCK 2012*, (May), 28–30.
- Smith, M. W. (2015). Direct acquisition of elevation data : Terrestrial Laser Scanning. *Geomorphological Techniques*, 1, 1–14. Retrieved from http://www.geomorphology.org.uk/geomorph_techniques
- Stock, G. M., Bawden, G. W., Green, J. K., Hanson, E., Downing, G., Collins, B. D., ... Leslar, M. (2013). Geosphere: High-resolution three-dimensional imaging and analysis of rock falls in yosemite valley, California. *Geosphere*, 9(2), 381.

- Strelec, S., Gazdek, M., & Mesec, J. (2011). Blasting design for obtaining desired fragmentation. *Tehnicki Vjesnik*, 18(1), 79–86.
- Sudhakar, J., Adhikari, G. R., & Gupta, R. N. (2005). Comparison of Fragmentation Measurements by Photographic and Image Analysis Techniques. *Rock Mechanics and Rock Engineering*, 39(2), 159–168.
- Tannu, N. S. (2017). *A Discrete Element Approach To Predicting The Uniaxial Compressive Response Of Plain Concrete*. The University of North Carolina.
- Tate, R. B., Ng, T. F., & Tan, D. N. K. (2008). Geological map of peninsular malaysia. Scale 1:1 000 000. Geological Society of Malaysia & University Malaya.
- Tatiya, R. (2017). *Ground and rock fragmentation – drilling and blasting. Civil Excavations and Tunnelling*.
- Teng, H. (2016). Coupling of Particle Blast Method (PBM) with Discrete Element Method for buried mine blast simulation. *14th International LS-DYNA Users Conference*, 1–12.
- Teza, G., Pesci, A., & Ninfo, A. (2016). Morphological analysis for architectural applications: Comparison between laser scanning and structure-from-motion photogrammetry. *Journal of Surveying Engineering*, 142(3), 1–10.
- Tiile, R. N. (2016). Artificial neural network approach to predict blast- induced ground vibration , airblast and rock fragmentation.
- TOPCON. (2015). GLS-2000.
- Ulusay, R., & Hudson, J. A. (2007). *ISRM Blue Book: "The Complete ISRM Suggested Methods for Rock Characterization, Testing and Monitoring:1974-2006*.
- Vasuki, Y., Holden, E. J., Kovesi, P., & Micklethwaite, S. (2014). Semi-automatic mapping of geological Structures using UAV-based photogrammetric data: An image analysis approach. *Computers and Geosciences*, 69, 22–32. Retrieved from <http://dx.doi.org/10.1016/j.cageo.2014.04.012>
- Wang, L. (2005). Support Vector Machines: Theory and Applications, 431.
- Windsor, C. R., & Robertson, W. V. (1994). Rock Reinforcement Practice,. *Volume 1, Rock Mass Formulation, 1*.
- www.malaymail.com. (2018).
<https://www.malaymail.com/news/malaysia/2018/02/05/perak-health-and-safety-dept-tells-quarries-to-buck-up/1570105>.

- www.malaymail.com.(2019).
<https://www.malaymail.com/news/malaysia/2019/06/10/chong-urges-sarawak-govt-urged-to-conduct-soil-integrity-study-in-quarry-op/1760769> [online].
- www.nst.com.my.(2018).
<https://www.nst.com.my/news/nation/2018/02/332276/more-half-quarries-perak-deemed-unsafe-dosh?fbclid=IwAR1b1zKW6h6P3YUI8s00ZYHYRP3kcFFUBNAu7etZNhCA5XfmdmIxnml7gzI>.
- www.thestar.com.my.(2008).
<https://www.thestar.com.my/news/community/2008/12/24/flying-rocks-damage-houses-in-taman-rawang-perdana> [online].
- www.thestar.com.my.(2019).
https://www.thestar.com.my/news/nation/2019/07/01/man-buried-under-tonnes-of-rock-in-quarry-incident?fbclid=IwAR1YG7aJ9AKURiXEMOU2ytcl2JeKRjdIXIr_8CpfSbRViwoE1tmjjMBYLdE.
- Wyllie, D. C., & Mah, C. (2017). *Rock Slope Engineering, Civil and Mining* (4th ed.). London and New York: Taylor & Francis Group.
- Xuefeng, L., Shibo, W., Shirong, G., Malekian, R., & Zhixiong, L. (2018). Investigation on the influence mechanism of rock brittleness on rock fragmentation and cutting performance by discrete element method. *Measurement: Journal of the International Measurement Confederation*, 113, 120–130.
- Yi, C., & Johansson, D. (2015). Discrete element modelling of blast fragmentation of a mortar cylinder. In *International Symposium on Rock Fragmentation by Blasting : 24/08/2015 - 25/08/2015*.
- Yi, C., Sjöberg, J., Johansson, D., & Petropoulos, N. (2017). A numerical study of the impact of short delays on rock fragmentation. *International Journal of Rock Mechanics and Mining Sciences*, 100(May 2016), 250–254.
- Yoon, J. (2007). Application of experimental design and optimization to PFC model calibration in uniaxial compression simulation. *International Journal of Rock Mechanics and Mining Sciences*, 44(6), 871–889.
- Zhou, J., Zhang, L., Yang, D., Braun, A., & Han, Z. (2017). Investigation of the quasi-brittle failure of alashan granite viewed from laboratory experiments and

grain-based discrete element modeling. *Materials*, 10(7).

Zhu, W. C., & Tang, C. A. (2006). Numerical simulation of Brazilian disk rock failure under static and dynamic loading. *International Journal of Rock Mechanics and Mining Sciences*, 43(2), 236–252.

LIST OF PUBLICATIONS

- i. Shahrin, M. I., Abdullah, R. A., Jeon, S., & Sa'ari, R. (2019). Calibration of Rock Uniaxial Compression Test using Discrete Element Method in LS-DYNA. *International Journal of Civil Engineering and Technology (IJCIET)*, 10(04), 975–984.
- ii. Shahrin, M. I., Abdullah, R. A., & Sa, R. (2018). A Review on Methods of Prediction Blasting Models on Rock Fragmentation in Quarry Blasting. In *The 4th ISRM Young Scholars' Symposium on Rock Mechanics (YSRM 2017) and The 5th International Symposium on New Development in Rock Engineering (NDRM 2017)*, Jeju, Korea.
- iii. Shahrin, M. I., Abdullah, R. A., Sa, R., Mustaffar, M., & Jeon, S. (2018). Integrating the Terrestrial Laser Scanning and Close Range Photogrammetry for Classification and 3D Modelling of a Quarry Face. In *The ISRM 10th Asian Rock Mechanics Symposium (ARMS10)*, Singapore.
- iv. Shahrin, M. I., Abdullah, R. A., Jeon, S., & Jeon, B. (2019). Numerical simulation of rock fragmentation by blasting using Discrete Element Method and Particle Blast Method. In *11th International Conference on Geotechnical Engineering in Tropical Regions (11th GEOTROPIKA) and 1st International Conference on Highway and Transportation Engineering (1st ICHITRA)*, Kuala Lumpur.
- v. Shahrin, M. I., Abdullah, R. A., Sa, R., & Alel, M. N. A. (2019). Effect of Burden to Hole Diameter Ratio on Rock Fragmentation by Blasting using LS-DYNA. In *Rock Dynamics Summit, Okinawa, Japan*.
- vi. Shahrin, M. I., Abdullah, R. A., Jeon, S., Jeon, B., & Sa, R. (2019). Calibration of rock Brazilian Test using Discrete Element Method in LS-DYNA. In *4th International Conference on Construction and Building Engineering (ICONBUILD) & 12th Regional Conference in Civil Engineering (RCCE)*. Langkawi, Malaysia.
- vii. Shahrin, M. I., Abdullah, R. A., Jeon, S., Jeon, B., Sa'ari, R., & Alel, M. N. A. (2019). Numerical Simulation on the Effect of Stemming to Burden Ratio on Rock Fragmentation by Blasting. In *The 5th ISRM Young Scholars'*

Symposium on Rock Mechanics (YSRM 2019) & International Symposium on Rock Engineering for Innovative Future (REIF 2019) Okinawa, Japan.

- viii. Rashid, A. S. A., Shahrin, M. I., Horpibulsuk, S., Hezmi, M. A., Yunus, N. Z. M., & Borhamdin, S. (2017). Development of sustainable masonry units from flood mud soil: Strength and morphology investigations. *Construction and Building Materials*, 131, 682–689.
<https://doi.org/10.1016/j.conbuildmat.2016.11.039>
- ix. Abdullah, R., Tsutsumi, T., Amin, M. F. M., Rashid, A. S. A., Khalfalla, F. A. I., Ahmed, U. A., & Shahrin, I. (2020). Evolution on deformation behaviour of brazilian test under different contact area using particle image velocimetry and finite element modelling. *Measurement*, 159, 107796.
- x. Abdullah, R. A., Syed Osman, S. M. B., Verankutty, N. J., Sulaiman, Z., Tsutsumi, T., & Shahrin, M. I. (2019). Evaluation of Tensile Behaviour for Rock Specimen. SAINS MALAYSIANA. (Reviewing process)