QUARRY BLAST EVALUATION SYSTEM FOR ROCK FRAGMENTATION

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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

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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 ketakselanjaran. Kemudian, sifat kejuruteraan batu diperoleh 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 diperoleh 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.

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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

Jv - Volumetric joint count

ε_r - Radial (lateral) strain

ε_a - Axial (vertical) strain

a - ½ length of ellipse

b - ½ width of ellipse

u - Horizontal displacement

k_s - Parallel-bond shear stiffness

k_n - Parallel-bond normal stiffness

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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 physicomechanical 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.

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