# ROCK MASS CLASSIFICATION FOR PREDICTING ENVIRONMENTAL IMPACT OF BLASTING ON TROPICALLY WEATHERED ROCK

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# DEDICATION

This thesis is dedicated to my father, who taught me that the best knowledge is that which is acquired for its own sake and through lifelong learning; to my mother, who taught me to value good human relationships, as a result of which I have friends the world over; and to my sister, who taught me that even the biggest task can be accomplished if done one step at a time. Although no more, their teachings live on and will continue to guide me as long as I live.

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# ABSTRACT

Tropical climate and post tectonic impact on the rock mass cause severe and deep weathering in complex rock formations. The uniqueness of tropical influence on the geoengineering properties of rock mass leads to significant effects on blast performance especially in the developmental stage. Different rock types such as limestone and granite exhibit different weathering effects which require special attention for classifying rock mass for blastability purpose. Rock mass classification systems have been implemented for last century for various applications to simplify complexity of rock mass. Several research studies have been carried out on rock mass and material properties for five classes of weathered rock-fresh, slightly, moderately, highly and completely weathered rock. There is wide variation in rock mass properties- heterogeneity and strength of weathered rocks in different weathering zones which cause environmental effects due to blasting. Several researchers have developed different techniques for prediction of air overpressure (AOp), peak particle velocity (PPV) and flyrock primarily for production blast. These techniques may not be suitable for prediction of blast performance in development benches in tropically weathered rock mass. In this research, blast monitoring program were carried out from a limestone quarry and two granite quarries. Due to different nature of properties, tropically weathered rock mass was classified as massive, blocky and fractured rock for simpler evaluation of development blast performance. Weathering Index (WI) is introduced based on porosity, water absorption and Point Load Index (PLI) strength properties of rock. Weathering index, porosity index, water absorption index and point load index ratio showed decreasing trend from massive to fractured tropically weathered rock. On the other hand, Block Weathering Index (BWI) was developed based on hypothetical values of exploration data and computational model. Ten blasting data sets were collected for analysis with blasting data varying from 105 to 166 per data set for AOp, PPV and flyrock. For granite, one data set each was analyzed for AOp and PPV and balance five data sets were analyzed for flyrock in granite by variation in input parameters. For prediction of blasting performance, varied techniques such as empirical equations, multivariable regression analysis (MVRA), hypothetical model, computational techniques (artificial intelligence-AI, machine learning- ML) and graphical charts. Measured values of blast performance was also compared with prediction techniques used by previous researchers. Blastability Index (BI), powder factor, WI are found suitable for prediction of all blast performance. Maximum charge per delay, distance of monitoring point are found to be critical factors for prediction of AOp and PPV. Stiffness ratio is found to be a crucial factor for flyrock especially during developmental blast. Empirical equations developed for prediction of PPV in fractured, blocky, and massive limestone showed $R^2$ (0.82, 0.54, and 0.23) respectively confirming that there is an impact of weathering on blasting performance. Best fit equation was developed with multivariable regression analysis (MVRA) with measured blast performance values and input parameters. Prediction of flyrock for granite with MVRA for massive, blocky and fractured demonstrated $R^2$ (0.8843, 0.86, 0.9782) respectively. WI and BWI were interchangeably used and results showed comparable results. For limestone, AOp analysed with model PSO-ANN showed $R^2$(0.961); PPV evaluated with model FA-ANN produced $R^2$ (0.966). For flyrock in granite with prediction model GWO-ANFIS showed $R^2$ (1) The same data set was analysed by replacing WI with BWI showed equivalent results. Model ANFIS produced $R^2$ (1). It is found the best performing models were PSO-ANN for AOp, FA-ANN for PPV and GWO-ANFIS for flyrock. Prediction charts were developed for AOp, PPV and flyrock for simple in use by site personnel. Blastability index and weathering index showed variation with reclassified weathering zones – massive, blocky and fractured and they are useful input parameters for prediction of blast performance in tropically weathered rock.

# ABSTRAK

Iklim tropika dan pengaruh tektonik lampau terhadap jasad batuan menghasilkan perubahan sifat geomekanik yang kompleks. Kesan daripada sifat-sifat geokejuruteraan ini menjadi pengaruh penting dalam kerja letupan batuan terutama dalam fasa pembinaan. Jenis batuan yang berbeza seperti batu kapur dan granit mempamerkan sifat yang berlainan serta memerlukan perhatian khusus terutamanya dalam pengelasan jasad batu untuk tujuan kerja letupan. Sistem pengelasan jasad batuan khusus bagi kerja letupan batuan terluluhawa tropika bertujuan memudahkan kerumitan penggunaannya bagi kerja letupan yang lebih selamat. Pengelasan sediaada terhadap status luluhawa batuan dibahagikan kepada zon segar, sedikit terluluhawa, sederhana, tinggi dan sepenuhnya boleh dikelaskan dengan lebih mudah untuk tujuan kerja letupan berdasarkan kepada sifat geomekanik batuan yang signifikan kepada tujuan kerja tersebut. Sifat jasad batuan yang tidak seragam dan luluhawa berbeza menyebabkan kesan kompleks terhadap hasil letupan terutama semasa kerja pembangunan. Pelbagai variasi pencirian batuan – kepelbagaian dan kekuatan batuan terluluhawa pada zon berbeza menyebabkan kesan alam sekitar disebabkan oleh letupan. Beberapa penyelidik telah membangunkan sistem ramalan letupan udara (AOp), halaju zarah puncak (PPV) dan batu liar terutamanya dalam letupan pengeluaran. Teknik-teknik ini mungkin tidak sesuai untuk ramalan prestasi letupan dalam keseluruhan spektrum batuan terluluhawa tropika. Dalam kajian ini, pemantauan letupan dijalankan di satu kuari batu kapur dan dua kuari granit. Oleh kerana sifat geokejuruteraan yang pelbagai dalam profil luluhawa, jasad batuan dikelaskan sebagai batuan masif, berbongkah dan batuan retak dalam penilaian dalam pembangunan prestasi letupan. Indeks Luluhawa (WI) diperkenal berdasarkan keliangan, penyerapan air dan indeks beban titik (PLI) batuan. Indeks Luluhawa, indeks keliangan, indeks penyerapan air dan indeks titik beban menunjukkan tren menurun daripada batuan masif ke batuan retak. Seterusnya Indeks Luluhawa Blok (BWI) dibina berdasarkan nilai hipotesis data eksplorasi dan model komputeran. Sepuluh set data letupan telah dikumpul untuk dianalisa dengan data letupan daripada 105 ke 166 per set data untuk AOp, PPV dan batu terbang. Untuk granit, setiap satu data dianalisa untuk AOp dan PPV dan lima set data dianalisa untuk batu terbang dengan input parameter yang pelbagai. Pelbagai teknik digunakan dalam meramal prestasi letupan seperti persamaan empirik, analisis regrasi pelbagai (MVRA), model hipotesis, teknik komputeran (AL, ML) dan carta grafik. Nilai yang diukur dalam prestasi letupan juga dibandingkan dengan teknik ramalan yang digunakan oleh penyelidik terdahulu. Indeks Peletupan (BI), faktor peledak dan Indeks Luluhawa didapati sesuai untuk meramalkan prestasi letupan. Caj maksimum bagi setiap detik dan jarak pemantauan dari sumber punca letupan adalah factor kritikal untuk ramalan AOp dan PPV. Nisbah kepejalan didapati sebagai faktor penting untuk meramalkan batu terbang terutamanya semasa pembangunan letupan. Persamaan empirik yang telah dibangun untuk ramalan PPV pada batu retak, bongkah dan batu kapur masif menunjukkan $R^2$ (0.82, 0.54 dan 0.23) menunjukkan bahawa terdapat kesan luluhawa terhadap prestasi letupan. Persamaan terbaik dibangunkan dengan analisis regrasi pelbagai (MVRA) dengan mengambil kira nilai prestasi letupan dan input parameter. Hasil jangkaan batu liar batu granit dengan kaedah MVRA bagi batuan masif, blok dan hancur, memberikan nilai $R^2$ sebanyak 0.8843, 0.86 dan 0.9782 masing-masing. Dengan menggunakan model jangkaan pula, nilai AOP dan PPV dibandingkan antara model ANN dan hibrid. Untuk batu kapur, AOp dianalisis dengan model PSO-ANN menunjukkan $R^2$ sebanyak 0.961; PPV yang dinilai dengan model FA-ANN menghasilkan $R^2$ (0.966). Bagi batu terbang granit dengan model ramalan GWO-ANFIS menunjukkan $R^2$ (1). Data set yang sama dianalisa dengan menggantikan WI dengan BWi menunjukkan keputuan yang sama. Model ANFIS menghasilkan $R^2$ (1). Model terbaik dalam menjalankan model ialah PSO-ANN untuk AOp, FA-ANN untuk PPV dan GWO-ANFIS untuk batu terbang. Carta ramalan dibina untuk AOp, PPV dan batu terbang untuk kegunaan di lapangan. Indeks letupan dan indeks luluhawa menunjukkan pengelasan semula zon luluhawa yang pelbagai – masif, bongkah dan batu retak dan input parameter berguna dalam meramal prestasi letupan untuk batuan terluluhawa tropika.

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# LIST OF ABBREVIATIONS

| | | |
|---|---|---|
| ABC | - | Artificial Bee Colony |
| AI | - | Artificial Intelligence |
| ANN | - | Artificial Neural Network |
| ANFIS | | Adaptive Neuro-fuzzy Inference System |
| AOp | - | Air Over Pressure |
| BART | | Bayesian Additive Regression Trees |
| BH | - | Bench Height |
| BI | - | Blastability Index |
| BQS | - | Blast Quality System |
| BRT | | Boosted Regression Trees |
| BTS | - | Brazilian Tensile Strength |
| CPM | - | Charge per meter |
| CW | - | Completely Weathered rock |
| DIF | - | Dip into the Face |
| DOF | - | Dip Out of the Face |
| DR | - | Density Ratio |
| DSR | - | Discontinuity Spacing Ratio |
| FA | - | Firefly Algorithm, |
| FIS | - | Fuzzy Inference System |
| GA | - | Genetic Algorithm |
| GBM | - | Gradient Boosting Machine |
| GMDH | | Group Method of Data Handling |
| GP | - | Genetic Programming |
| GPR | - | Gaussian Process Regression |
| GSI | - | Geological Strength Index |
| GWO | - | Grey Wolf Optimizer |
| HD | - | Hole Depth |
| HW | - | Highly Weathered rock |
| HOR | - | Horizontal (joints. discontiutities) |
| ICA | | Imperialist Competitive Algorithm |
| JA | - | Joint Aperture |
| JPS | - | Joint Spacing |
| JPO | - | Joint Plane Orientation |
| JTL | - | Joint Trace Length |
| KNN | - | k-Nearest Neighbours |
| MARS | | Multivariate Adaptive Regression Splines |
| ML | | Machine Learning |
| MR | - | Multiple Regression |
| MVRA | - | Multi-Variable Regression Analysis |
| MW | - | Moderately Weathered rock |
| PF | - | Powder Factor |
| PoI | - | Porosity Index |
| PLI | - | Point Load Index Strength |
| PLIR | - | Point Load Index Strength Ratio |
| PPV | - | Peak Particle Velocity |
| PSO | - | Particle Swarm Optimization |
| RD | - | Rock Density |
| RF | - | Random Forest |
| RFNN | - | Recurrent Fuzzy Neural Network |

| | | |
|---|---|---|
| RMD | - | Rock Mass Description |
| RQD | - | Rock Quality Designation |
| RMR | - | Rock Mass Rating |
| SD | - | Scaled Distance (for prediction of AOp or PPV) |
| SGI | - | Specific Gravity Index |
| SHRN | - | Schimdt Hammer Number |
| SM | - | Statistical Methods |
| SNF | - | Strike Normal to the Face |
| SR | - | Stiffness Ratio (BH/B) |
| ST | - | Stemming Height |
| SVM | - | Support Vector Machine |
| SW | - | Slightly Weathered rock |
| TCR | - | Total Core Recovery |
| TLBM | - | Teaching–Learning-Based Optimization |
| UCS | - | Uniaxial Compressive Strength |
| UTM | - | Universiti Teknologi Malaysia |
| VOD | - | Velocity of Detonation |
| WaI | - | Water Absorption Index |
| XG Boost | - | eXtreme gradient boosting; |
| XML | - | Extensible Markup Language |

# LIST OF SYMBOLS

a - Site constant
AF1 - Adjustment Factor 1 for BI by Ghose (1988)
AF2 - Adjustment Factor 2 for BI by Ghose (1988)
$\alpha$ - Site Constant for prediction of AOp
$\beta$ - Site Constant for prediction of AOp
$\theta_0$ - drill hole angle
B - Burden
C - Maximum Charge per delay
d - Hole diameter
E - Young’s modulus
F - Fresh rock
g - Gravitational constant
H - Site constant (for calculation of AOp)
$H_m$ - Mohr’s Scale of hardness
K - Site constant (for calculation of AOp)
$K_N$ - Void ratio
$K_r$ - Weathering coefficient
$K_W$ - Water Absorption Ratio
$K\varphi$ - Factor of safety ( for calculation of flyrock)
Lm - Maximum rock projection (m)
Lmax - maximum ejection distance (m)
ls Stemming length in meters
m Charge per meter
n - Site constant (for calculation of AOp)
N - Number of rows for blasting
$Po_2$ - Porosity (%) of weathered rock
$Po_{MAX}$ - Maximum porosity (%) of completely weathered rokc
S - Spacing
$T_b$ - Size of rock fragment in m
W - Weight of explosives per delay (for calculation of AOp)
$Wa_2$ - Water absorption (%) of weathered rock
$Wa_{MAX}$ - Maximum Water absorption (%) of completely weathered rock

# LIST OF GLOSSARIES

Burden
Spacing
Hole diameter
Bench height
Subgrade
Power factor
Ground vibration
Flyrock
MVRA
AI
Development blasting
Production blast

# LIST OF APPENDICES

# CHAPTER 1

# INTRODUCTION

## 1.1 Background

In July 2013, a blasting incident in Seri Alam, Johor terrorised the nation. The terror did not just end there. In July 2015, a second blasting took place at a construction site in Batu Pahat, Johor (Edy Tonnizam et al., 2013, 2016). These explosions killed several people and left others with serious injuries. Additionally, these blasting had damaged properties worth millions of Ringgit Malaysia. Investigations revealed that both accidents resulted from the site personnel's inability to identify weak geological structure (Edy Tonnizam et al., 2018). Besides, researchers had also claimed that geological inconsistency and sudden abnormality had resulted in flyrock accidents (McKenzie, 2009; Raina et al., 2015).

Rock mass classification has been widely used for more than a century in various applications of rock engineering design such as tunnelling, foundation, slopes, rippability, and excavatability. Rock mass classification is essential as it simplifies the complexity of actual rock mass into intelligible units (Singh and Goel, 1997). Moreover, it is a powerful instrument in the feasibility of design (Stille and Palmström, 2003).

During blasting operation, approximately 15 to 30% of the released energy is exclusively used for the fragmentation and displacement of the rocks (Armaghani et al., 2013; Khandelwal and Monjezi, 2013). On the contrary, the remaining 70-85% of energy causes an undesirable environmental impact such as air overpressure (AOp), ground vibration, and flyrock in the surrounding areas (Hanispanah et al., 2018). On the other hand, less than 1% of the energy may be sufficient to cause a flyrock during the blast (Adhikari, 1999). Various techniques had been developed to predict the blasting performance and compare it to the measured value. The projection of the blasting performance is based on a wide range of the input parameters of the blasting. From 1960 to 2000, the extrapolation of the blastability was correlated to the empirical equations. Researchers had theorised that both ground vibration and AOp with empirical equations depend on the blast designs. Lilly (1986) introduced the concept of blastability index based on the site-specific rock mass properties, which in turn could be correlated to the powder factor.

Ghose (1988) developed a blastability index for the coal-bearing strata based on the rock mass properties, and stiffness ratio, which was to the powder factor. On the other hand, the Julius Kruttschnitt Mineral Research Centre (JKRMC, 1996) introduced the blastability concept mainly for the coal-bearing rocks based on the size and strength of the rock block to get the desired fragmentation. Nevertheless, such a technique was not possible to be adopted for every site. In contrast, Lu (1997) introduced a concept of blastability based on the energy required to convert the situ block size into a blasted block size. Scholars had also developed the indexed systems for blastability based on rock mass and material properties (Latham and Lu, 1999; Azimi et al., 2016). Therefore, most of the blastability indices developed since 1986 were for general blasting.

Multivariable regression analysis (MVRA) provides better results than empirical equations (Hasanipanah et al., 2017). This is mainly because the empirical equations use the blast design parameters whereas MVRA utilises more of the input parameters, which include rock mass and material properties (Armaghani et al., 2016; Fouladgar et al., 2017). During the last decade, many researchers had established artificial intelligence (AI) models to predict the environmental effect as a result of the blasting (Armaghani et al., 2019). AI models can predict better results with nonlinear input parameters.

There is a significant deterioration in the physical and geomechanical properties during the process of weathering near the earth’s surface under varied climatic conditions (Tugrul, 2014). Thick and deep weathering profiles are observed in the tropical region (Shaw, 1997). The variation of the rock mass and material properties demands special attention and classification in the blasting application, specifically during the developmental stage.

The development blast is usually carried out in near-surface during earthwork whereas the production blast is done on the developed benches (Lee and Kim, 2016). Nonetheless, it is a challenging task to develop horizontal benches because the topography and thickness of the weathered rock vary in the developmental area. Therefore, the stiffness ratio has always been an issue in the developmental blast. Abrupt changes in material and mass properties usually exist in thick tropically weathered rock, especially in the completely weathered (CW) to moderately weathered (MW) zones. The prediction of blasting operation and its impacts on the environment during the developmental stage is highly imperative Thus, there is a need to prepare guidelines or predictive regimes for the blasting of the weathered rocks to simplify the operations carried out by field personnel who are directly involved in the blasting process.

## 1.2 Problem Statement

The geomechanical properties and geological features of the rock mass have great influence in the blasting operations. The complexity of these parameters become crucial when the tropical rock mass is subjected to different degrees of weathering. On the other hand, the effects of the blasting operation depend on the fracture patterns and the heterogeneity of the rock mass.

Blasting effects include the AOp, ground vibration and flyrock, which affect the environment and its surroundings. It is common for the blasting process to involve a wider spectrum of weathering zones in the developmental stage of earthwork. The issues during this stage include a lower drilling depth, variable length of burden, weak geological structures at the blasting face, and the heterogeneity of the rock mass. These issues create obstacles in the blast design as a result of the insufficient stemming of the length or burden. Therefore, it is necessary to address the issues of tropical rock mass for the process of developmental blast. The existing rock mass classification for the purpose of blasting may need specific refinements to cater to the unique issues in the tropically weathered rock environment. Furthermore, it is imperative to examine the correlation between the exploratory qualitative parameters of the tropically weathered rock and the blasting performance. Besides, it is significant to improvise the prediction accuracy of the environmental effects with the measured values. Hence, a better prediction of the blast performance techniques, which include input parameters such as tropical weathering, blast design, and blastability is needed for better accuracy. The technique has to be simple for site personnel to practice as they are the ones who are directly involved in the blasting process.

## 1.3 Objectives

The aim of this study is to investigate the uniqueness of the tropical rock mass and its material properties that influence the environmental effects of the blasting such as AOp, peak particle velocity (PPV), and flyrock distance, to develop the best prediction model for this issue. Therefore, the subsequent objectives were designed to achieve the purpose of the present study:

i. To investigate tropical rock mass profile that contributes to the performance of development blast.

ii. To determine significant factors of tropically weathered rock properties that influence blast performance.

iii. To develop a unique rock mass classification system for blastability of the tropically weathered rock.

iv. To develop a method to predict the blasting effect of tropical rock mass to the environment.

## 1.4 Scope of the Study

The present study selected a limestone quarry in Thailand and two granite quarries in Johor, Malaysia because they were located in the tropical region. All three quarries were fully operational and met the requirements of the construction aggregates. Furthermore, the developmental area had a series of variable bench heights in the highly weathered (HW) and CW rocks. Besides, the benches in the production area were well developed with uniform heights from the MW to the fresh (F) rock.

This study examined the rock mass properties of the weathered igneous and sedimentary rocks identified based on numerous studies. Next, a method was selected to investigate the weathering zones in the field and identify similar rock mass properties, based on the conducted review. Researchers had tested the various physical and mechanical properties of the weathered rock in the laboratory. This study included simple physical and mechanical properties of the weathered rock to develop the weathering index. The block weathering index was developed based on the analysis of the exploration data. This study further compared the weathered rock mass and material properties to each degree of weathering and to each parameter, which was assigned into five groups based on these properties. The weight among these parameters was based on the inter-relationship of the individual parameter in a complete data set. The 3-Dimensional (3D) block model was developed based on exploratory data samples via the Surpac software. The processed output of the individual block in the 3D block model has been designated as block weathering index.

From 1960 to 2000, the development of blastability was assessed significantly. The production of blast performance was mainly based on empirical equations and blast design parameters. Therefore, this study compared the blastability indexes designed by Lilly (1986) and Ghose (1988). The blastability index consisted of five input parameters that were scrutinised to determine the environmental effects as a result of blasting. This study reviewed Christaras and Chatziangelou (2017) blasting quality system for widely, intermediate, and closely spaced joint spaces. Next, this study identified the research gap to develop the rock mass classification system in the tropically weathered rock. The data collection method at the field was developed based on the evaluation of previous literature on environmental data for the AOP, PPV, and flyrock blasting. Similarly, the input parameters were selected from the works of literature on the prediction of blast performance. Then the data collection was carried out for a year and six months. It included field observations of environmental effects as a result of the blasting at three quarries, sample collection, and laboratory testing.

This study examined the existing rock mass classification systems that were still in practice for different applications such as tunnel system, excavation, and slope stability to identify the research gaps. Therefore, the classification for tunnel system and slope stability is related to the rock mass supporting against gravity. Meanwhile, the classification for excavatability depends upon the equipment, which is being used. As a result, a rock mass classification system for blastability of the tropically weathered rock was developed in this work. Then the multivariate regression analysis (MVRA) was used to develop the equations because the empirical equations that predicted the blast performance failed in terms of accuracy. Hence, the MVRA technique is a benchmark to evaluate performances based on different techniques. In the last decade, researchers had employed AI techniques to develop models that predict the blast performance. Nevertheless, recently, the hybrid AI and machine learning (ML) models were developed to predict blast performance. AI models were used to predict the AOp and ground vibrations. On the other hand, ML models were mainly used to predict flyrock. Therefore, the best computational models for AOp, PPV, and flyrock were evaluated.

The scope of the study is limited to 3 quarries in the tropical region, 10 data sets, developmental blast with a maximum of 166 blasting events per data set.

## 1.5 Research Questions

Researchers had studied the process of weathering in tropically weathered rocks for multiple geomechanical problems. For the last six decades, many researchers had developed the performance of general blasting, specifically on production blast. The blast performance evaluation is crucial and therefore, the latest techniques need to be incorporated to increase its accuracy. The following questions were framed for this research:

i. Which key tropical rock mass properties or structural characteristics influence the blast performance for AOp, ground vibration, and flyrock?

ii. What are the properties of granite and limestone that influence the performance of developmental blast?

iii. How does the blast design determined by various tropically weathered zones influence the performance of the developmental performance?

v. How do the different prediction methods accurately forecast the performance of the developmental blast?

## 1.6 Significance of Research

The prediction of blast performance in a specific rock had been researched extensively for a long time globally. The existing prediction methods on blast performance are chiefly employed for general blasting and not specifically for the tropically weathered rock mass in development blasting. Therefore, the following are the advantages or benefits expected from this research project:

i. The geoengineering properties of tropical rock mass for blasting will be catalogued. This significant contribution will benefit the civil and mining engineering works. Therefore, Malaysia will stand in the forefront as a research hub for studies that involve tropical rock masses.

ii. The engineers will understand the effects and possible mechanics of blasting in the tropically weathered rock mass. This knowledge will, therefore, minimise the inappropriate blast design, in which the tropical rock mass is involved.

iii. Society will experience visible benefits based on their understanding of the potential risk of blasting tropical rock mass. Hence, this knowledge will increase the safety factors, especially when dealing with excavation via blasting.

iv. A systematic approach that assesses blasting sites based on geoengineering aspects will be considered in the process of blasting design. Based on the economic scale, a good blasting design will minimise the risk of environmental effects such as flyrock, ground vibration and AOp.

## 1.7 Definition of Terms

Blasting is essential for works pertaining to hard rock excavations in the mining and civil engineering project areas. Listed below are the common terms related to blasting and the techniques to predict the blast performance in the present study.

| | |
|---|---|
| **Burden**<br>(Bhandari, 1997) | Shortest distance from the free face. Expressed in m |
| **Spacing**<br>(Rai and Imperial, 2005) | Distance between holes parallel to the face. Expressed in m |
| **Hole diameter**<br>(AyalaCarcedo, 2017) | The diameter of the blast hole. Expressed in mm |
| **Bench height**<br>(Bowa, 2015) | The height of the bench along which excavation is done. Expressed in m |

| | |
|---|---|
| **Subgrade**<br>(Adhikari, 1999) | Drilling, which is done below the bench height to avoid the toe. Subgrade drilling is about 10 to 15% of bench height. Expressed in m |
| **Power factor**<br>(Amini et al., 2012) | The weight of explosives consumed per tonne of rock generated due to blasting. Expressed in kg per tonne. |
| **Airover Pressure**<br>(Singh and Sinha, 2013) | Air pressure created due to the movement of rock during blasting is known as airover pressure. Expressed indB. |
| **Ground vibration**<br>(Khandelwal and Singh, 2007) | Vibration due to blasting, which is created as a shock wave in the ground or rock mass and transmitted through the ground. It does not cause permanent deformation. Expressed mm/sec |
| **Flyrock**<br>(Kecojevic and Radomsky, 2005) | The undesired throw of rock fragment during blasting at the quarry or civil projects. It is measured from the centre of a blast to the maximum distance travelled by the rock fragment. Expressed in m |
| **MVRA**<br>(Kleinbaum et al., 1988) | The best-fit equation is developed for the measured parameter with the coefficient values for each independent variable or input parameter. It is also known for the widening of the simple regression concept. |
| **AI**<br>(Negnevitsky, 2005) | Intelligence demonstrated by computers through systematic investigation motivated by humans for a given problem through learning and solving. |
| **Development blasting**<br>(Bhanadari, 1997) | The blasting carried out during the developmental stage at the near-surface, which has the variable depth of blast holes with varying weathering stages |

| | |
|---|---|
| **Production blast** (Siskind et al., 1980) | Blasting carried out where the normal consistent depth of blast holes that exist in well-developed benches to achieve maximum production |

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