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Flyrock in Surface Mining

Origin, Prediction, and Control

Autar K. Raina

Flyrock in Surface Mining

This book provides a comprehensive understanding of historical and recent research, with a critical review of several aspects of the flyrock phenomenon, along with the classification of pertinent literature. This puts flyrock into proper perspective and develops a comprehensive regime for flyrock prediction and control. It also addresses the blast danger zone demarcation based on scientific understanding in comparison to the consequence-based approach supported by pertinent case studies.

Features:

- Discusses exclusive material on flyrock in surface mining.
- Presents comprehensive and critical review of the flyrock phenomenon.
- Reviews prediction and control mechanisms in vogue with scientific and risk-based definitions of blast danger zone.
- Provides new insights into the flyrock definitions, prediction, and prevention along with the research approach to the problem.
- Includes Indian case studies and summarizes global data available in the published domain.

This book is aimed at researchers and graduate students in mining and civil engineering, engineering geology, and blasting.

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Dedication

Dedicated to Dada (Late Dr. Ashoke Chakraborty), who pushed me to limits; Prof. B.B. Dhar, Babosh and Maa, Bhaiya and Bhabhi—who saw me through thick and thin.

An accident is a chain of events . . .

Anon.

"Improvements are cumulative, then any improvements that we make in our blast planning and executing assuredly will enhance the Quality of our blasting safety. We can rapidly advance our improvement by benchmarking, emulating the best practices. It is essential for the leadership of our explosives industry to underscore the crucial importance of continued blasting safety training for supervisors overseeing blasting operations, for blasters and for the personnel working in blasting crews. Alone, safety training is a paper tiger. We must instill in every blasting person a safe attitude, the sine qua non necessary to achieve the Quality performance standard for blasting safety, zero accidents."

—Brulia (1993)

Author's Take on Flyrock

When things are perfectly engineered the system behaves, but still falters for uncertainties . . . as a rule . . . even if the mine-mill fragmentation system is fully engineered, the uncertainties in the rockmass, human intervention, and explosives provide enough reasons for a fragment to shoot out.

To me flyrock is far more dangerous than ground vibrations. It can damage, injure, and even kill. I am still at loss to understand why people have spent a fortune in ground vibration predictions.

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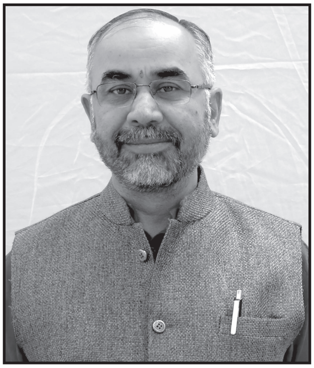

Autar K. Raina is at present working as Chief Scientist in the Mining Technology Department at Nagpur Research Center of CSIR-Central Institute of Mining and Fuel Research, India. He is also Professor at the Academy of Excellence in Scientific and Innovative Research (AcSIR), India. A gold medalist in Post Graduate studies, he has a Ph.D. in Mining Engineering from IIT-ISM, Dhanbad and M.Sc., M.Phil., and Ph.D. in Geology from the University of Jammu, India, to his credit. He is a recipient of the coveted National Mineral (now Geosciences) Award from the Ministry of Mines, Government of India, in addition to several other awards, certificates of merit, and appreciations from the industry for different contributions to rock blasting and use of IT in Mining. With a research experience of more than 25 years in several aspects of blasting like fragmentation, human response to blasting, flyrock, and ground vibrations, he has published more than 150 papers in national and international journals with 16 papers on the subject of flyrock. He has several books, book chapters, and edited chapters on rock blasting to his credit and is on the reviewer panel of several international journals of repute. He has conducted research on several aspects of blasting and selection methodology of tunnel boring machines through several government-funded research projects. He has guided several students for their Ph.D., M.S., and B.E. dissertations. Fragalyst—a digital image analysis software for blast fragmentation measurement—has been consistently upgraded by him for the advantage of mining industry along with other IT apps for rockmass classification and blast design like Blast Design and Database Analysis System (BD2MAS) wherein he has several patents and copyrights to his credit.

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Preface

In modern times of internet, ever-growing information, and its flow, it is practically difficult to compile any document that qualifies as a book. The daily increasing scenario of citations makes the task more difficult. Despite this, there are references that qualify as classical works and there are just others which receive little attention or have little content. At the same time, one cannot be oblivious of yesterday's works that might not have caught the attention of the authors but have significant content. Despite this, there are certain questions in science that are pertinent and require a sustained introspection. The author is aware of the fact and the topic of the book chosen is akin to present-day surface mining.

Blasting is important and rather a dominant method of rock excavation, even today. There are several outcomes of blast into which the energy provided by the explosives on detonation gets split up. The major portion of this energy is consumed by ground vibrations and air overpressure. Little energy is used to fragment and heave the rock broken under the influence of explosive pressures. Least energy is however, in some cases, manifested in the form of rock fragments travelling beyond planned distances. Such fragments, known as flyrock, have gained importance after the author of this book provided new insights into the phenomenon with several instances to model the behaviour.

Flyrock has received little attention until 2014 and has recorded a significant growth in its prediction and control thereafter. Since flyrock has a potential to cause fatalities, it should have received significant attention, but the facts are contrary. Vibrations and air overpressure have been dealt with by researchers in detail, though it can only damage the structures and has a nuisance value. The difficulty in acquisition of sufficient data, reporting constrained by the known statutory consequences, occurrence by chance, and difficulty in defining the predictive regime of flyrock can be some of the reasons for the bias, if not otherwise. The multiple mechanics involved in the generation, launch, travel, and landing of a flyrock are additional complications that face the researchers.

The prediction of flyrock is still a herculean task as one cannot produce flyrock for testing, and even if this is tried, there is no guarantee that flyrock will occur in a test. This specifically eludes the researchers and makes it very difficult to predict the same. Unlike fragmentation, throw, and vibrations from blasting, flyrock is an uncertain event. Also, if a flyrock is generated, whether it will travel in a direction of concern and hit any object or person and what could be the level of damage are all uncertain quantities. So, the phenomenon of flyrock has several associated probabilities that not only makes the task of flyrock event and its travel distance difficult to predict but places constraints on defining the blast danger zone around a proposed blast. This has resulted in many regulations that are just flyrock event based and present little scientific explanation. In addition, the consequences are extremely difficult to quantify as lot of subjectivity is involved, particularly if flyrock hits a person. Thus, the consequences are difficult to quantify. However, the probabilities and consequences can together be framed into a network to provide an insight into the risk involved due to flyrock. The method has an advantage that it can allow a dynamic blast danger zone, in contrast to the static zones, about the mines, and in turn allow mining of precious minerals, very close to the habitats. Accordingly, this book has been compiled with focus on literature and its review and to provide means and define terms that can be used by researchers to control the flyrock. In brief, the book is addressed to the students and planners for poking into the issue rather than providing a holistic solution to the problem.

I hope that students and researchers along with field engineers and legislators, who are interested in blasting with a keen interest in the flyrock, will find the book a useful one. I am expecting response on the work, different new propositions and concepts, from seekers of the subject and critics.

The approval of Director, CSIR-Central Institute of Mining and Fuel Research, India, and the financial aid in the form of grant for a research project from the Ministry of Mines, Government of India, are acknowledged by the author. This book would not be possible without active support of my office and its staff, particularly at Nagpur Research Center, both scientific and technical. The help rendered by them is praiseworthy. Umpteen number of people from various mining sectors in India helped in data acquisition and provided all sorts of support that is worth mentioning.

My gratitude to Dr. Chakraborty who introduced me to the topic and facilitated several studies. Prof. VMSR Murthy, my Ph.D. guide at IIT-ISM, Dhanbad, critically examined several of my works that proved valuable in shaping this book. Prof. Agne Rustan provided several critical inputs and encouragement. Dr. Saša Stojadinović, Prof. R.N. Gupta, Dr. P. Pal Roy, Dr. A. Sinha, Prof. Arvind K. Mishra, Dr. A.K. Soni, Prof. P. Rai, Dr. Bhanwar, Dr. Suresh Sharma, and Dr. K. Ram Chandar deserve thanks for their contributions. Bhushan, Shantanu, Late Arup, Pawan, Harsha, Rohan, and many of my associates deserve mention for their active help. Anand, Rishi, Dr. Narayan, and many associated fellows deserve special mention for their last moment help. Kusum, Baijee, Acharya Motilal, Jaya maasi, and Prof. Maharaj Pandit deserve special mention for their contributions in my career. Last but not least, my ardhangini Rimple, daughter Medhu, and son Muppu supported me through sharing the time that belonged to them.

Symbols

Δ_t	length of impulse time (s) of flyrock
Δp_τ	adjustment for pressure in Pa for burden distance
A	area of flyrock fragment in m^2
B	burden (m)
B_{ob}	optimum breakage burden
B_c	critical burden (m)
b_d	drag factor (dimensionless)
b_{sd}	specific drilling ($1/m^2$)
B_{sd}	scaled depth of burial of explosive (metric system)
$C(E)$	consequence of an event
c_d	velocity of detonation (m/s)
c_{dc}	confined velocity of detonation (m/s)
c_{di}	ideal velocity of detonation (m/s)
C_f	correction factor (used in throw to account for flyrock)
c_{pi}	p-wave velocity or longitudinal wave velocity (m/s), measured *in situ*
c_{Si}	s-wave velocity or transverse wave velocity (m/s), measured *in situ*
C_x, C_D	drag coefficient (dimensionless)
d	diameter of blasthole (m)
d_c	diameter of cartridge (m)
d_e	diameter of explosive (m)
E	modulus of elasticity or Young's modulus (Pa or GPa)
E'	Gurney's constant
E_{lq}	linear energy of the explosive charge in $\times 10^3$ J/m
f	target impact frequency (impact/year)
f_p	pattern footage
g	acceleration due to gravity in m/s^2
H_1	maximum height (m) along a distance R_h
H_2	maximum height (m) along a distance R_t
H_b	height of bench (m)
H_i	the height of rise in m at any given horizontal distance measured relative to the original elevation of the fragment
I_{BI}	Blasting Index (fragmentation oriented)
	j, k_1, k_2, and k_3 proportionality constants
J_{fr}	joint frequency rating
k_{50}	mean fragment size
k_c	characteristic fragment size
k_f	size of flyrock (m)
k_{opt}	optimum fragment size
K_v	velocity coefficient
k_x	size of the fragment (nominal diameter, m)
L	length of flyrock fragment (m)
l_{bh}	length of borehole or blasthole (m)

L_f	shape factor of flyrock
l_o	backbreak (depth) (m)
l_q	length of charge (m)
l_s	length of stemming (m)
l_{sd}	length of stemming between deck charges (m)
l_{sub}	subdrilling length
m	mass of flyrock fragment (g, kg)
M_e	mass of explosive in one blasthole (kg)
m_l	total mass of material per unit of length (kg/m)
M_r	mass of rock blasted by one blasthole ($\times 10^3$ kg)
n	slope of a function
N_b	total number of blasts per year
N_{ff}	number of free faces
O_j	joint orientation (°)
p	pressure (Pa)
$P(E)$	probability of a flyrock event
$P(R)$	probability of wild flyrock travelling the target distance
$P(T)$	probability of wild flyrock travelling on an impact trajectory
$P(T_e)$	probability of target exposure
p_a	probability of a person being hit by a flyrock
p_b	pressure acting on the flyrock fragment at escape (Pascal)
p_{bc}	near field pressure (Pa or MPa) from blasthole measured in rock at a distance from blasthole
Q	explosive weight (kg)
q	specific charge or old powder factor (kg/m^3 of rock)
q_a	charge factor or load (kg/m^2)
Q_h	mass of explosive charge (kg) in a blasthole (also called as charge per hole)
q_l	linear charge concentration (kg/m)
R	distance from blasthole or blast site to a measuring point (m)
R_0	the curve characteristic
r^2	coefficient of determination (dimensionless)
R_{dc}	decoupling ratio (dimensionless)
R_e	distance of excess throw or length (m) (includes displacement of much smaller number of fragments)
R_f	maximum horizontal flyrock distance (m)
R_{fpt}	maximum horizontal flyrock distance in pressure–time method (m)
R_h	distance travelled by the flyrock along a horizontal line at the original elevation of the rock on the face (m)
R_h	the horizontal distance along the trajectory in m
R_m	distance of throw or throw length (m) of considerable amount of fragmented rock from blast face (m)
R_n	Reynolds number (dimensionless)
R_{obj}	distance of object of concern from the blast site (m)
R_{opt}	optimum throw (m), throw distance for efficient loading of muck by equipment (m)

R_{perm}	permissible or acceptable distance of flyrock (m)
R_t	total distance travelled by a fragment ejected from the blast accounting for its heights above the pit floor (m)
R_T	throw of blasted rockmass (m)
S	spacing between blastholes (m)
S_a	visible surface of a person (for flyrock impact)
S_j	rock joint spacing (m)
t	time (s)
t_{HH}	delay between two blastholes
T_r	threat ratio
t_{RR}	delay between two rows in a blast
v	velocity
V	volume (m^3)
v_0	initial or exit velocity of flyrock fragment (m/s)
V_h	volume of blasthole
W	width of flyrock fragment (m)
W_b	width of bench
W_j	energy required to crush unit weight of rock (J)
W_r	energy absorbed to fragment a unit weight of rock (J)
W_s	seismic energy generated per unit weight of explosive (J)
Z	acoustic impedance of material ($kg/m^2/s$)
Z_e	acoustic impedance of explosive ($kg/m^2/s$)
Z_r	acoustic impedance of rock ($kg/m^2/s$) measured in situ
θ	launch angle of flyrock (°)
π	3.14159
ρ_e	density of explosive before charging (kg/m^3) or g/cm^3
ρ_{ee}	effective in-hole density of explosive (kg/m^3)
ρ_r	density of rock (kg/m^3)
σ_c	uniaxial compressive strength (MPa) (estimated from Schmidt hammer)
Φ	angle of breakage (°)
α	muck angle (°)
α_{bi}	blasthole angle (°)
α_{opt}	optimum muck angle (°)
η_a	gas viscosity coefficient under movement
μ	Poisson's ratio
μ_{air}	air drag (m/s^2)—negative
ρ_{fluid}	the fluid mass density kg/m^3

Acronyms

ACO	ant colony algorithm
AIME	American Institute of Mining, Metallurgical, and Petroleum Engineers
ANFIS	adaptive neuro fuzzy inference system
ANFO	ammonium nitrate and fuel oil
ANN	artificial neural networking
ANN-ADHS	ANN coupled with adaptive dynamical harmony search
ANN-HS	hybrid ANN models coupled by harmony search
	AusIMMAustralasian Institute of Mining and Metallurgy
BBO	biogeography-based optimization
BDZ	blast danger zone
BN	Bayesian network
BRT	boosted regression tree
CA	cultural algorithm
CART	classification and regression tree
CFR	Code of Federal Regulation (USA)
CIM	Canadian Institute of Mining, Metallurgy and Petroleum
COA	cuckoo optimization algorithm
DA	dimensional analysis algorithm
DE	differential evaluation
DF	detonating fuse
DGMS	Directorate General of Mines Safety (India)
DNN	deep neural network
DP	drilling pattern (Rectangular or staggered)
DT	decision tree
DTH	down-the-hole hammer (drills)
ELM	extreme learning machine
EMLM/BN	ensemble machine learning method/Bayesian network, algorithm
ET	explosive type
FBPNN	feedforward back propagation neural network
FCM	fuzzy cognitive map
FFA	firefly algorithm
FoS	factor of safety
FRAGBLAST	shortened form for International Symposium on Fragmentation by Blasting
FRES	fuzzy rock engineering system
Fuzzy	fuzzy logic
GA	genetic algorithm
GDP	gross domestic product
GEP	genetic expression programming
GOA	grasshopper optimization algorithm

GP	genetic programming
GP/GEP	gene expression programming
GSI	Geological Strength Index
GWO	grey wolf optimization
ICA-ANN	imperialist competitive algorithm
ICGCM	International Conference on Ground Control in Mining
ILO	International Labour Organization
IOM3	Institute of Materials, Mineral and Mining—accessed through ISEE OneMine portal (members only portal)
ISEE	International Society of Explosive Engineers
ISEE ODB	International Society of Explosive Engineers Online Database
ISRM	International Society for Rock Mechanics and Rock Engineering
KELM	kernel extreme learning machine
LMR	linear multiple regression
LOO	leave one out cross-validation method
LS-SVM	least squares support vector machines
LWLR	local weighted linear regression
MARS	multivariate adaptive regression splines
MAS	motion analysis software
MHA	metaheuristic algorithm
ML	machine learning
MLR	multiple linear regression analysis
MMFS	mine-mill fragmentation system
MRMR	mining rockmass rating
ms	millisecond when used to classify detonators and delay periods
MSWA	multichannel seismic wave analyser
MWD	measure while drilling
NeSt	non-electric shock tube initiation device
NG-ANN	neurogenetic artificial neural network
NIOSH	National Institute for Occupational Safety and Health
OC	objects of concern
OR-ELM	outlier robust-ELM
PCA	principal component analysis
PCR	principal component regression
PETN	pentaerythritol trinitrate
PSO	particle swarm optimization
RF	random forest
RFNN	recurrent fuzzy neural network
RMSE	root mean square error
RQD	rock quality designation
RSA	response surface analysis
RSM	response surface methodology
SAG	semi-autogenous
SAIMM	Southern African Institute of Mining and Metallurgy
SEM	probabilistic structural equation model
SME	Society for Mining Metallurgy and Exploration

SVM	support vector machine
SVR	support vector regression
TOPSIS	technique for order preference by similarity to ideal solution
USBM	United States Bureau of Mines
WOA	whale optimization algorithm
XRD	X-ray diffraction

1 Introduction

Mining that consumes most of the explosives to date has a tremendous role in society as it not only contributes to the world GDP, but also forms the core of the industrial revolution, as metals and minerals are also produced from mines. No sphere of life on this planet is untouched by mining, including IT, as the basic hardware used in electronics has inking of minerals.

Excavations are places where rockmass is removed for a variety of purposes. In some cases of excavations, only soil or soft rock is encountered that can be removed by mechanical devices like excavators. However, in many cases of excavations, hard rock is met, which needs to be broken and dislodged, before it can be lifted, loaded, and transported. If explosives are used to break such rock to facilitate easy loading and hauling, it is termed as blasting. Hence, blasting is a method of rock breakage used in different types of excavations and is a well-established technique that has been used since times immemorial. Blasting is the core of the mining activity world over.

The objectives of blasting in the diverse projects vary and depend on the final desired outcome of the planned application. In civil structures, it is used to create space for hosting surface or underground structures like foundations, tunnels, defence installations, nuclear power plants, nuclear waste repositories, and underground space creation, in addition to the production of construction material and dimensional rocks. However, the objective of blasting in mines, which produce minerals, is to fragment the rock to achieve a desirable size in tune with the system requirements and at the same time throw and heave the broken rock into a particular profile which is economically feasible for lifting or loading, transportation or hauling, and further breaking by mechanical means to achieve the desired size of fragments. In addition, there are a multitude of applications of blasting, most of which have been compiled in Figure 1.1. Although mechanical methods of excavation are gaining pace with the introduction of efficient tunnel boring machines and roadheaders, blasting continues to be the major method of rock breakage, considering its comparative economical advantage over other methods. It will not be out of place to mention that blasting, which encompasses creation of space or production of minerals, is part of our daily life.

For a common man, blasting entails explosive, threat, and danger to life. Terrorism is also deeply connected with explosives, which for the sake of human interest has not been described further. However, for a blasting engineer, the word "blasting" denotes a complex process of breakage of rockmass through interactions of products of detonating explosive with rockmass for its removal aimed to benefit the humanity and of course, production-related profitability. Accordingly, our focus will be on mining as mines consume the maximum quantities of explosives. The explosive market is estimated to grow from $18,000 million in 2021 to $22,000 million by 2028.[1] Deployment of such volume of explosive in mining also means consequent high-probability dangers associated with blasting.

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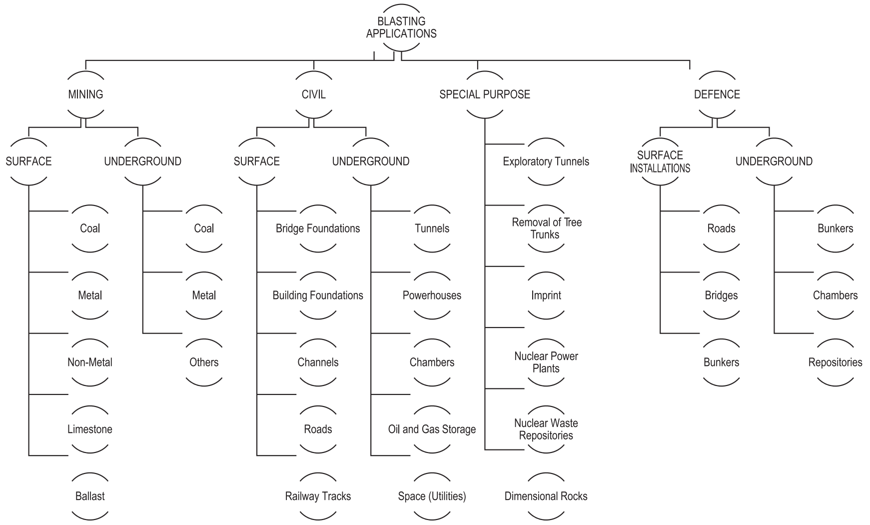

FIGURE 1.1 Broad spectrum of application of blasting in various types of projects.

Blasting in mines through the science of rock breakage has progressed significantly in recent years. With the advent of supercomputing, advanced numerical methods, high-fidelity sensors and high-speed data acquisition systems, interdisciplinary studies, and artificial intelligence methods, the findings related to explosive-induced breakage of rocks have yielded tangible results for field deployment. To drive the topic in hand, it is imperative to have a broad idea of what is being discussed. A blast design props up even at the stages of feasibility and detailed project report formulations for a mining project or even civil works of varied types. The requirement of annual production volume defines the daily production demand in mines and as such, the volume of rock that needs to be blasted at a time. This defines several other components like the drill diameter, the shovel, and the hauler capacities and hence the blast design, as will be explained further. Blast design once tested and accepted in actual conditions transforms into a production pattern.

1.1 BLASTING BASICS

Blasting, or chemical excavation method, involves application of explosive energy to fragment and throw rock. Bhandari (1997) provided a complete information on the explosive energy partitioning and its utilization by productive and unproductive results of blasting. It is believed that only a fraction of energy, supplied to the rock by the explosive, is utilized in fragmenting and throwing the rock to a distance, and most of this energy is transformed into ground vibrations and air overpressure. It may be pointed out that the energetics of a blast is a very complicated subject owing to high speed of explosion in a blast, instant release of energy, and its rapid dissipation. However, there are cases which document the components of the energy entering different domains. An energy transfer efficiency test called the "cylinder expansion test" introduced by Ouchterlony et al. (2004) claims to quantify the partitioning of explosive energy into various components and provide the details of the energy transmission and conversion into seismic, kinetic, and fragmentation energies.

Sanchidrián et al. (2007) concluded that 2–6% of the total available energy is expended in the form of fragmentation, 1–3% for the seismic energy, and 3–21% for the kinetic energy. They added that for a confined blasthole, the seismic energy was 9% of the heat of explosion. Calnan (2015) claimed to account for 73% of the total explosive energy available in a blasthole that included energies for borehole chambering (13%), rotational kinetic energy (25%), translational kinetic energy (5%), and air overpressure (28%) and concluded that borehole chambering, heave, and air blast are the largest energy components in a blast. However, Comeau (2019) argued that major energy may be consumed in crushing to generate particles of <1 mm size and hence estimation of quantity of fines generated is important while providing fragment size distributions during measurement.

One important assertion about blasting is that explosives used in breakage do not know the rockmass and in turn rockmass does not know the explosives. The interaction starts when an explosion takes place in a blasthole. The enormous amount of energy in the range of 10–15 GPa, confined in a blasthole, on release, starts the talk with the rockmass. The huge blasthole pressures that are confined can be held in a blasthole over a very short span of time ranging from few microseconds to few milliseconds. During this process, two major mechanisms come into play.

1. The shock due to sudden release of energy or simply the detonation pressures interact with the rockmass being loaded.
2. The borehole pressure due to highly confined gases try to escape through least resistance paths in multiple ways.

The shock is believed to create fractures in the rockmass and consumes maximum pressure generated by the explosive (Cunningham, 2006) and creates a zone of breakage zone about the blasthole modelled by Esen et al. (2003). The blasthole pressure gets activated simultaneously or with a delay of fraction of second which is believed to expand the existing or newly formed cracks and produce further fragmentation and displaces the fragmented rock to a distance forming a muckpile. The phenomenon is discussed in detail by Mortazavi and Katsabanis (2000) and Sim et al. (2017). A complete description of the blasting fracture mechanics, the theoretical foundations, and its application in rock breakage can be found in Zhang (2016). Different recent studies have focused on impact of various factors like role of initiation point (Long et al., 2013), rockmass discontinuity orientation and their dip on process of burden breakage (Ash, 1973; Mortazavi & Katsabanis, 2000), effect of in situ stresses on rock breakage (Yi et al., 2018), and rock-explosive interactions (Raina & Trivedi, 2019).

Irrespective of the said facts, it is believed that a very small fraction to the tune of 1% of the explosive energy of a blast may propel rock fragments to undesired distances and can be dangerous (Berta, 1990). However, none of the recent research has mentioned the energy component transformed to flyrock, probably because it is not a regular outcome of a blast and is restricted to poor design, human factors, special conditions of rockmass, or malfunctioning of the pyrotechnic delay elements.

Such rock fragments emanating from a blast, travelling beyond expected distances called flyrock, are the subject of this work. However, before describing the details, it is good to understand what are the objectives of blasting?

1.2 BLASTING OBJECTIVES

As mentioned earlier, the major objectives of blasting are to break the rockmass, displace it from its in situ position, and to throw the broken rock fragments up to a desired distance and a heap of proper shape, for efficient loading and hauling (Figure 1.2).

The rockmass fragmented by blasting needs to be loaded and transported in an economical way. Hence, the two outcomes of blasting, viz. fragmentation and heave, are of prime importance to a blasting engineer, as these define the economics of a mining operation. This means that the broken material should be of required size and the blasted muck should be casted in a profile that is favourable to the loading equipment, and, in relevant terms, they are in tune with the requirements of the mining subsystem or the system.

Accordingly, blasting cannot be seen in isolation being part of a complete system and its outcome significantly affects the economics of the downstream operations. Blasting is thus a unit operation of a larger system, generally called as mine–mill fragmentation system (MMFS; Figure 1.3), mine to mill system, or drill to mill system. There are two subsystems of "mine" and "mill" in the said system. Metal and non-metal mines generally operate the full MMFS, but coal mines fall within mine

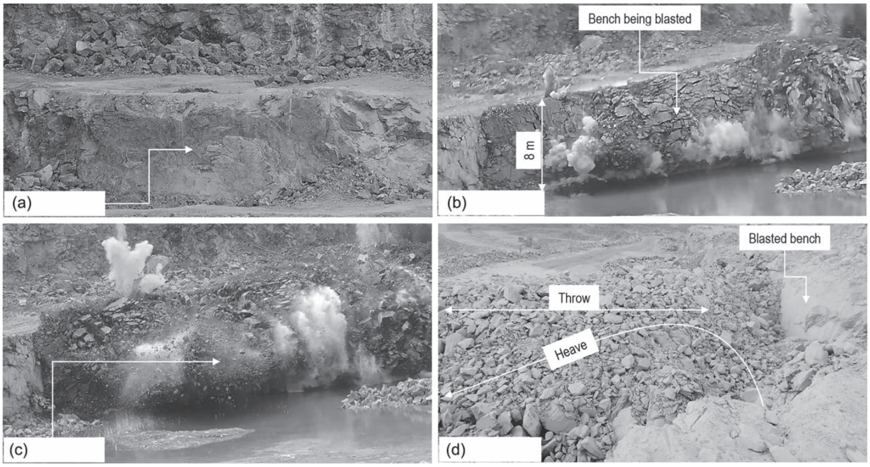

FIGURE 1.2 The processes of breakage and throw due to blasting in a surface mine. (a) Blast bench. (b) Rock breakage in progress (bench being blasting). (c) Throw of the broken rockmass (muck) to a distance. (d) Throw (distance) and heave or final shape of the broken material.

subsystem only. Owing to the economic requirements and environmental constraints, the objectives of blasting can be further described as follows:

1. Breaking of rock by explosives can yield anything, from dust to huge boulders. Fragmentation requirements vary from mineral to mineral. The basic principle is that large equipment is not made to handle large fragments of muck, but to handle large volumes of the blasted material. Too small fragments will involve excessive handling and also reduce the value of ore, and too large fragments will significantly hamper the productivity (Cunningham, 2019). The specifications of loading equipment and size of crusher generally dictate the requirement of fragment size from blasting and hence their optimization. Fragmentation is generally defined in terms of mean fragment size (k_{50}) and the uniformity index (n) assessed with the help of Rosin and Rammler (1933) distribution or Swebrec distribution (Ouchterlony, 2005).
2. Throw is an important requirement for loading as it defines the muck profile or heave and is generally measured in terms of muck profile angle (α). An optimum muck angle (α_{opt}) is different for different loading equipment and depends on the basic operational mechanism of the loading equipment, i.e. whether the loader digs and loads or just scrapes and loads. The looseness of the muck and angle of the muck will define the performance of the loading equipment directly and the hauling equipment indirectly. One of the important aspects of throw of the material during blasting and its impact on ore dilution is described in detail by Gilbride et al. (1995).
3. The presence of people, structures, and other facilities, referred to as objects of concern (OCs) and defined later, within and outside the mine is of concern during blasting. The proximity of such object(s) constraint the blasts in terms of weight of explosives used in a hole and in a delay to control ground vibration and air overpressure within the stipulated limits. Such limits are dependent on excitation frequency of the vibrations and the nature of the structure influenced by blast vibrations. The explosive quantity used in a blasthole also influences the flyrock travel distance.

Moreover, there are conflicts in the cost equations of the unit operations (Calnan, 2015; Comeau, 2019; Mackenzie, 1966; Ouchterlony et al., 2004) and hence a mine–mill fragmentation system (MMFS; Figure 1.3), as defined by Hustrulid (1999a), demands optimization.

There are several works of interest that have provided various methods and means to define the MMFS optimization that in general translates into blast fragmentation optimization. Few such references along with some case studies are compiled in Table 1.1 for the inquisitive reader.

To achieve the fragment size determined by the system, it is imperative to have a proper blast design that yields the economically viable fragment size. It is important to understand that the philosophy of a blast design varies significantly for underground and surface blasting. In the case of underground blasting, a free face must be created, as it is available in surface (mine or bench) blasting.

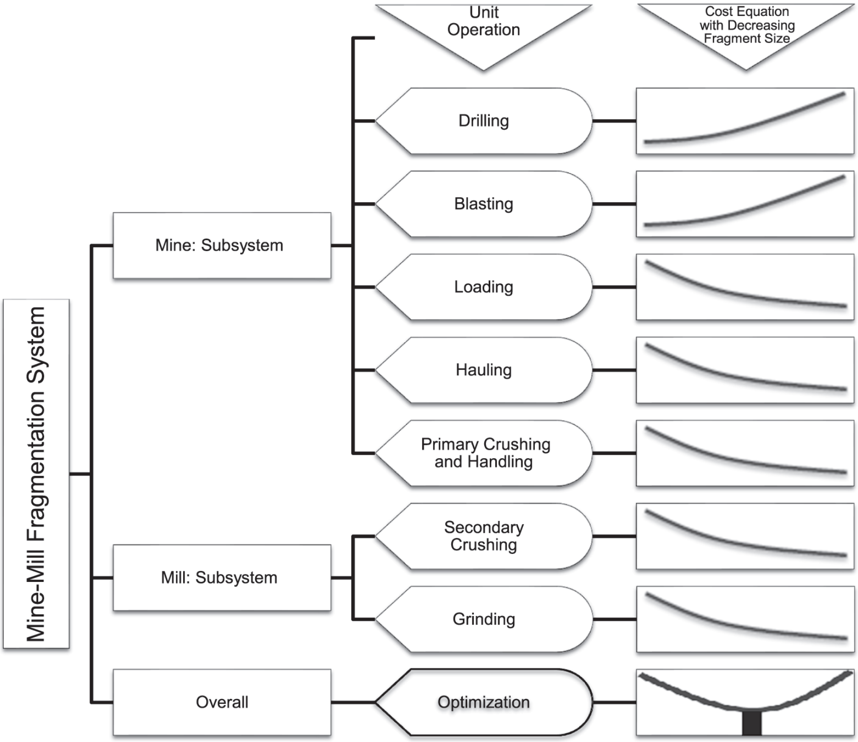

FIGURE 1.3 Mine–mill fragmentation system explained; the alignment of the unit operation arrows points to the change in the cost of the unit operation with change in fragmentation from small to large size (representative trends only).

A significant number of books, texts, and publications, available online and offline, exist on methods of blast design engineering and system optimization. There are quite a few online platforms that claim to work towards optimization of fragmentation through proper engineering and database management systems. Surface blast principles are, however, dealt with in detail by Hustrulid (1999a, 1999b) that include almost all the design considerations, particularly, fragmentation, heave, role explosives, and accessories like delays in the process of rock breakage. On the face of it, one may feel that the design process is intricate and quite complex. However, it will not be out of place to mention that the design process of blasting is not as complicated as it appears. An attempt is hence made here to understand the design process in simple terms.

1.3 BLAST DESIGN

The basic requirements of productivity of a mine are very simple to grasp as the annual production and availability of working hours and equipment can be simply put to work to define the production requirements of a mine, as explained in Figure 1.4.

TABLE 1.1

Some Important Mine–Mill Fragmentation System Optimization Works by Few Researchers

S. No.	Citation	Focus	Details
1	Mackenzie (1966)	Blast optimization	This is a classical study defining and setting the trend for blast fragmentation optimization. The concept was further analysed and detailed by Hustrulid (1999a)
2	Hagan and Just (1974)	Rock breakage theory and optimization	Discusses in detail the breakage by explosive, the role of rockmass, blast design, and explosives on rock fragmentation; muckpile and its impact on economics
3	Morrell and Munro (2000)	JKMRC model application	Describes the use and prediction capabilities of the model for MMFS optimization in three mines
4	Grundstrom et al. (2001)	MMFS optimization	A case study of Porgera gold mine reporting significant improvements in productivity
5	Scott et al. (2002)	MMFS optimization constraints	Reviews the literature on fragmentation optimization. Stress the proper identification of cost-savings in different unit operations in mine-to-mill process and role of experienced manpower to handle such analysis
6	Jankovic and Valery (2002)	Case study on MMFS optimization	Used extensive data to demonstrate the role of analytics and blasting data for cost optimization and report 4–5% increase in the mill by using such strategies
7	Chakraborty et al. (2004, 2005)	Fragmentation evaluation	Comprehensive studies on evaluation of rockmass and blast design variables and their relative importance in defining the fragmentation during blasting and the system optimization routine
8	Esen et al. (2007)	MMFS optimization	Defined a method called process integration and optimization involving benchmarking, rock characterization, measurements, modelling/simulation of blasting and comminution processes, and/or material tracking to achieve best throughput
9	Raina (2013)	Basics of fragmentation optimization	Describes the basics of fragmentation optimization and how it is to be achieved
10	Nageshwaraniyer et al. (2018)	Energy-based method for MMFS optimization	A case study of copper mine economic analysis of unit operations. Spectral imaging was used for tracking, material handling network, and stochastic power consumption in mine-to-mill operations. Economic analysis model was developed for cost-saving

(Continued)

TABLE 1.1 (Continued)

Some Important Mine–Mill Fragmentation System Optimization Works by Few Researchers

S. No.	Citation	Focus	Details
11	Erkayaoglu and Dessureault (2019)	MMFS optimization using data mining and neural networks	Data mining and use of random forest and adaptive boosting algorithm for optimization of mine-to-mill for control and analysis of drilling- and blasting-related variables influencing the productivity
12	Leng et al. (2020)	Oversize and toe formation	Statistical constitutive model developed to evaluate the formation of oversize fragments and toe formation in blasting. Role of satellite holes assessed with the help of numerical method
13	Messaoud et al. (2020)	Oversize production	Microlevel investigations in rock microfabric properties using XRD and microscopic grain identification methods to define the production of oversize fragments in blasting. Statistical methods used for defining optimization of fragmentation due to blasting
14	Assegaff et al. (2020)	Uniform fragmentation	Uses statistical methods to optimize the fragmentation for obtaining uniform fragment size in blasting
15	Park and Kim (2020)	MMFS optimization using MWD technique	A case study of MMFS optimization using monitoring while drilling (MWD) data. Penetration rates were derived from blastholes to work out the intact rock properties and predict the breakage efficiencies influencing comminution energy. Tensile strength and Bond work index correlated with the penetration rate data for crushing and grinding efficiencies
16	Fang et al. (2021)	Fragmentation modelling	Firefly technique has been used for optimization of blast fragmentation and efficacy of the model discussed in comparison to the other artificial intelligence methods used for such operations
17	Zhang and Luukkanen (2021)	Feasibility of MMFS optimization	Discussed the studies that have been successful and unsuccessful in MMFS optimization owing to evaluation of energy efficiency, microcracks in blasting, and redistribution of energy from blasting to milling. The feasibility of MMFS optimization is discussed

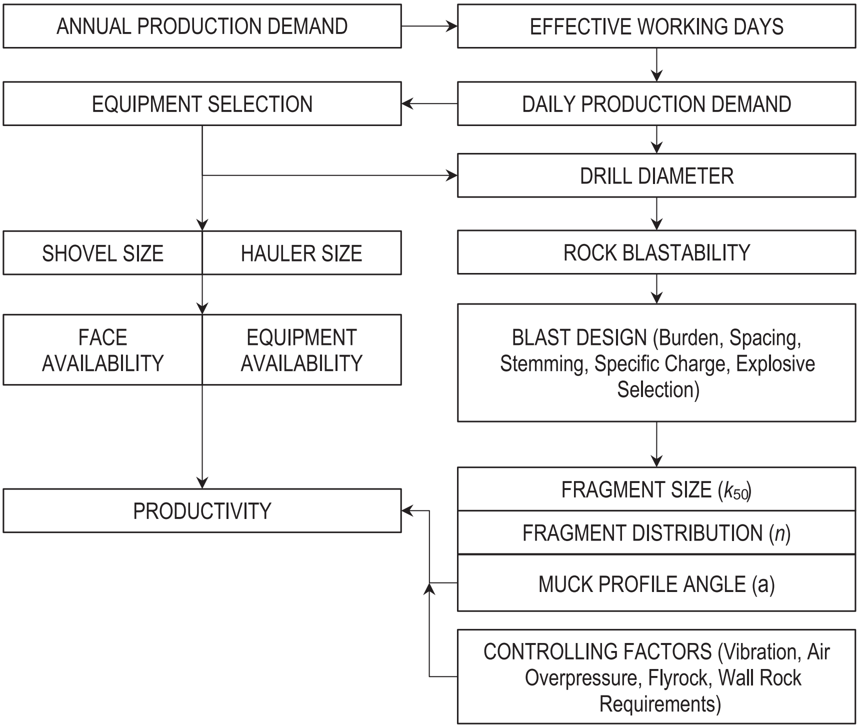

FIGURE 1.4 Basic requirements of productivity in mines. The process involves a comprehensive analysis of requirement of productivity, equipment, and scale of blasting along with its controls.

A brief perusal of Figure 1.4 reveals that the productivity in a mine is pivoted on the blast design, as it determines the degree of fragmentation and hence the productivity of the MMFS. It will not be out of context to explain the terminology, as provided in Figure 1.5, that is important before discussing blast design. As far as possible, the definitions given hereunder, their explanations, and symbols have been adopted as recommended by the ISRM (Rustan et al., 2011).

Free Face

> *"Free face, an unconstrained surface almost free from stresses, e.g., a rock surface exposed to air or water or buffered rock that provides room for expansion upon fragmentation. Sometimes also called open face."*

Blasthole

> *"Blasthole, a cylindrical opening drilled into rock or other materials for the placement of explosives." Please note that it is used as a single term and not as "blast hole."*

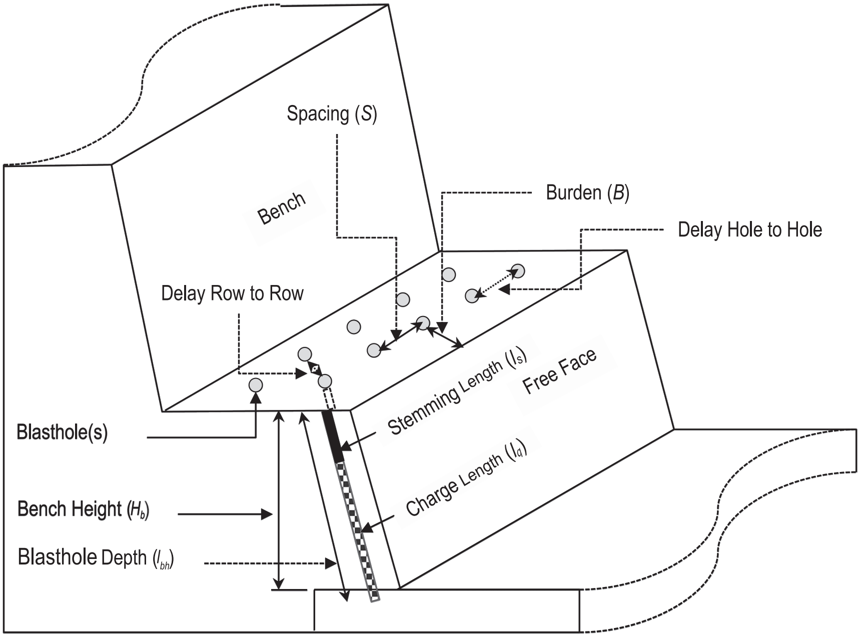

FIGURE 1.5 Basic design variables of a blast in surface mine operations.

BLASTHOLE INCLINATION OR ANGLE

> *"Blasthole inclination (α_{bi}), (°), the angle between the blasthole and a reference plane, normally the horizontal plane."*

BLASTHOLE LENGTH

> *"Blasthole length (l_{bh}), (m), the length of the blasthole as measured along the axis from the collar to the bottom of the hole."*

BENCH HEIGHT

> *"Height of bench (H_b), (m), the vertical distance between the floor and top level of a bench."*

SUBDRILLING LENGTH

> *"Subdrill, length of blasthole drilled below the planned level of breakage at the floor in bench blasting. subdrilling length (l_{sub}), (m), the length of subdrilling."*

BURDEN

> *"Burden in bench blasting (B), (m), shortest perpendicular distance between the centre line of a charge and the free or buffered face."*

> *Burden has several variants as follows:*
>
> *"Burden in crater blasting, blasted burden (true or effective burden) (B_b), (m), critical burden in bench or crater blasting (B_c), (m), drilled burden (B_d), maximum burden (B_{max}), optimum burden (B_{opt}), optimum breakage burden (B_{optb}), optimum fragmentation burden (B_{optf}), practical burden (B_p), reduced burden (B_r).*
>
> *For explanations, please see Rustan et al. (2011).*

SPACING

> *"Spacing (S), (m), distance between boreholes in a row. It is necessary to distinguish between spacing in drilling (S_d) and spacing in blasting (S_b)." The variants are as follows:*
>
> *"Spacing in blasting (S_b), (m), the distance between holes initiated on the same delay number. In some blasts when all holes are initiated with different delays the spacing in blasting is defined as the distance between holes detonated consecutively. Spacing in drilling (S_d), (m), the distance between adjacent holes in a row of holes located parallel to the blast front or free surface."*

STEMMING

Stemming length (l_s) (m), the length of stemming, is the length of the blasthole at its collar that is not filled with explosives and is packed with inert material as defined herein:

> *Stemming, the inert material of dense consistency, such as drill cuttings, gravel, sand, clay, or water in plastic bags, which is inserted in the collar of the drill hole after charging and used to seal the hole temporarily in order to prevent venting of gas, increase blasting efficiency, to reduce air shock waves or dampen any open flames. In coal mining water stemming cartridges work very well as they also contribute to minimise dust and fires. Stemming is also used as a material to separate explosive charges in a borehole (decks). Stemming can also be used to seal off open cracks intersecting the blasthole.*

SPECIFIC CHARGE

Specific charge (q) (kg/m^3) or (kg/t) is the consumption (planned or actual) of explosive per cubic metre or metric ton of rock.

HOLE-TO-HOLE DELAY

Hole-to-hole delay (t_{HH}) is the time delay used between two adjacent blastholes in order to fire these at different timings.

ROW-TO-ROW DELAY

Row-to-row delay (t_{RR}) is the time delay used between adjacent rows so as to fire the holes at different timings.

OBJECTS OF CONCERN

Objects of concern (OCs) are objects that are amenable to blast-induced damage, injury, or fatality and are detailed later.

BLAST DANGER ZONE

Blast danger zone (BDZ) is the zone around blasting, generally stipulated or fixed by regulatory authorities, that must be secured and cleared of OCs before blasting. Special permissions are required to blast within BDZ.

1.3.1 UNDERSTANDING THE BLAST DESIGN

To design a simple blast, a few rules may be sufficient to understand the same. The process will include the following:

1. Assessing the rockmass blastability preferably in terms of its density and p-wave velocity that define its impedance. There have been attempts to classify rockmass for blasting in terms of rock factor or rock constant "*c*" by umpteen number of authors. However, a comprehensive review of blastability can be traced to Salmi and Sellers (2021). A scheme for assessing the blastability is also provided in Section 1.3.2.
2. Fixing of the drill diameter which is generally dictated by the bench height and production requirements. However, if a drill with prefixed diameter is already in place, it will constraint the design process.
3. Selection of explosive by knowing its characteristics like its density (ρ_e) and velocity of detonation (c_d). This will be determined by the rock type. A broad criterion is to match the explosive impedance ($c_d \times \rho_e$) with the impedance of the rock, i.e. the product of density of rock and p-wave velocity ($\rho_r \times c_p$).
4. Predicting the initial fragment size through established equations of mean fragment size (k_{50}) and uniformity index (n) of the fragment size distribution.

Thus, the drill diameter (d) in conjunction with the blastability of the rockmass and fragmentation size requirements defines the blast design since one of the major blast design variables, burden (B), is directly related to it (Ash, 1990; Konya & Walter, 1991)—see Figure 1.4.

The variables of blast design that get defined in the process include the burden (B), the spacing (S), and the stemming length (l_s):

$$B = k_b \times d \tag{1.1}$$

TABLE 1.2
Representative Values of Parameters for Major Blast Design Variables

Parameter	Minimum	Average	Maximum	Comments, Use
k_b	25	–	40	Minimum for very hard rock and maximum for highly jointed soft rock
k_s	1.0	1.25	2.0	Minimum for uniform and controlled fragmentation, average for general blasts, and maximum for rockmass that requires simple dislodgement
k_{ls}	0.6	0.7	1.0	Minimum generally not recommended if flyrock is a concern, average for general blasts, and maximum for controlled blasts

$$S = k_s \times B \tag{1.2}$$

$$l_s = k_{ls} \times B \tag{1.3}$$

The practical values and the range of parameters of k_b, k_s, and k_{ls} in Equations 1.1, 1.2, and 1.3, respectively, are given in Table 1.2.

Another simple method for blast design, that incorporates density of rock and explosive, corrections for number of rows, geological conditions, and other conditions, is provided by Konya (1995). Once the design is ready, the fragmentation can be evaluated with the help of Equation 1.4, called the Cun–Kuz model (Cunningham, 2005):

$$k_{50} = c \times q^{0.8} \times Q^{1/6} \times \left(\frac{115}{S_{wr}}\right)^{19/30} \tag{1.4}$$

where k_{50} is the mean fragment size (cm), c is the rock factor or constant varying between 0.2 and 22 and can be estimated with the help of Equation 1.8, q is the specific charge (kg/m^3) defined as the ratio of total explosive used in kg to the total volume of blast in terms of product of B, S, and bench height, Q is the explosive weight (kg), and S_{wr} is the relative weight strength of explosive relative to ANFO (ammonium nitrate fuel oil).

With moderate changes in blast design and experimentation thereof, the optimum fragment size and blast design can be identified to draw a production pattern. Simulations or trial and error method with proper planning can be put to work for establishing the best pattern along with blast design iterations (Hustrulid, 1999a). Further requirements of throw and reduction of other unwanted effects can be taken into consideration by changing the hole-to-hole and row-to-row delays and even modifying the blast design. The aforementioned method will require measurement of fragmentation that is economically viable.

1.3.2 Rockmass and Blast Design

Rockmass is a very complex subject as it involves several inherent properties that puzzle the excavation engineer. Engineers, however, need to predict the outcome of the blast process that demands conversion of the rockmass and explosive into numbers. However, explosive characteristics can be achieved by measurements, as explained further in Section 1.3.3. Putting rockmass to numbers is not only a very subjective matter but also a complex topic. The inherent variability of rockmass in terms of its strength, jointing, and microscopic properties makes it fuzzy and qualitative in nature. Frequent spatial changes of rockmass properties add to the difficulty of rockmass characterization. Consequently, a host of classifications, methods, and rating systems for rockmass blastability, that defines the ease with which a rockmass can be fragmented by blasting, have been developed over the years. To have a broad idea of the complexity in rockmass classifications and blastability, a list of rockmass properties (both macroscopic and microscopic), their nature, and the feasibility of converting them to numbers is presented in Table 1.3.

The role of microscopic properties in blasting and their incorporation in classification systems is practically lacking or has been confined to laboratory or numerical analytical studies only determining the strength of the intact rocks (Abdlmutalib & Abdullatif, 2019; Ahmad et al., 2017; Dobereiner & de Freitas, 1986; Jeng et al., 2004; Kamani & Ajalloeian, 2019; Messaoud et al., 2020; Tsidzi, 1990).

The macroscopic properties of rockmass have been treated fairly that resulted in summation of such individual properties with development of rating or classification systems. Accordingly, there have been multiple attempts to group these into classification systems to define the classes of the rockmass for ascertaining stability of the rockmass in underground excavations by employing the macroscopic variables. Some such classifications that have been widely used for mining and excavation purpose are rockmass rating or RMR (Bieniawski, 1989), rock quality designation (RQD) (Deere & Deere, 1989), index of rock quality or Q (Barton et al., 1974), mining rockmass rating (MRMR) (Laubscher & Jakubec, 2001), geological strength index (GSI) (Marinos et al., 2005), and rockmass index or RMi (Palmström, 1996). These classification systems are functions of strength of intact rock and adjusted for block volume or joint density, joint roughness, joint alteration, joint size, and many other such properties. RMi is probably the first such classification that incorporates blastability of rockmass but has not been used for the purpose because of complexity in calculations. Aforementioned systems are known as geomechanics rockmass classifications.

There are some examples of use of rockmass classifications for defining the outcome of blasting, but such studies are restricted to quality of blasting (Innaurato et al., 1998) impact on controlled blasting (Singh, 2003), prediction of overbreak (Jang & Topal, 2013; Koopialipoor et al., 2019; Segaetsho & Zvarivadza, 2019), and blast overpressure (Gao et al., 2020) in mining or civil excavations. Also, such studies are negligible and have not been widely accepted by field engineers for defining the blastability of the rockmass. Adhikari et al. (1999) based on a significant database of an underground cavern contested the findings of Ibarra et al. (1996) that the performance of underground blasts like overbreak and underbreak can be compared

TABLE 1.3
Comprehensive Evaluation of Rockmass for Engineering Purpose and Problems Faced in Quantification of Rockmass

Macroscopic Properties	Nature/Comments	Microscopic Properties	Nature/ Comments
Intact rock strength	Quantifiable, compressive, and tensile strengths of intact rock can be determined in laboratory	Grain size	Quantifiable
Rockmass strength	Difficult to quantify owing to the presence of joints and joint properties	Grain fabric	Fuzzy
Lithology	Varies significantly over space, presents difficulties in characterization in linear excavations like tunnels	Grain boundary	Fuzzy, fractal
Number of joints	Quantifiable	Boundary strength	Difficult to quantify
Joint spacing	Quantifiable, multiple joints association create confusion. Which joint to be considered is an issue	Grain shape	Quantifiable but difficult to include in definitions
Weathering	Qualitative, quantification is not practical		
Joint length	Quantifiable		
Joint strength	Quantifiable, cohesion, and friction angle needs detailed testing		
Joint alteration	Qualitative, difficult to put to numbers		
Joint filling	Qualitative, difficult to put to numbers		
Joint aperture	Quantifiable, fuzzy	Fuzzy indicates the variations are not crisp but overlap in different classes	
Joint roughness	Fuzzy, fractal		
Block size	Quantifiable, varies over a wide range, restrictions due to joints occurring in different planes	Fractal means that the distributions have fractal nature	
p- and s-wave velocities	Quantifiable, have significant role as blasting, and these properties are of dynamic nature. Define impedance, in situ determination requires a lot of expertise		

to rockmass quality "Q" of Barton et al. (1974). Only a few works report the use of such classifications in flyrock modelling, e.g. use of *RMR* (Bakhtavar et al., 2017; Hasanipanah & Amnieh, 2020; Monjezi et al., 2011, 2012; Wu et al., 2019) and GSI (Asl et al., 2018).

Although some of the properties considered in such classifications can be used in assessing blastability, the use of such classifications in totality needs further evaluation, despite the fact that some recent studies (Nur Lyana et al., 2016; Sayevand & Arab, 2019) have used such classifications for defining fragmentation. In order to compare the role of rockmass on fragmentation, Doucet et al. (1996) conducted limited number of experiments. Despite no significant relationship, they observed that the characteristic particle size after blasting (k_c blast) increases when the characteristic size of the in situ distribution (k_c in situ) increases and that k_c of blast decreases when the adjusted powder factor or specific charge increases.

The energy-block-transition model (Lu & Latham, 1998) defines blastability through a comprehensive mathematical treatment of transformation of in situ block size to fragmented block size. They considered 12 factors, viz. uniaxial compressive strength, uniaxial tensile strength, density of rock, static or dynamic modulus of rock, p-wave velocity, Schmidt hammer rebound value, Poisson's ratio, fracture toughness of rock, mean in situ block size, fractal dimension of in situ block sizes, wave velocity ratio, the ratio of p-wave velocity in field to that in laboratory or by rock quality designation (RQD), and cohesion or friction angle of discontinuity plane for defining the blastability. However, they (Lu & Latham, 1998) ignored the role of joint orientation, although Chakraborty et al. (1994) had observed that the mean fragment size along with depth and cross-sectional area of broken zone were significantly impacted by the joint orientation.

Zhang (1990) developed a fivefold classification system for blastability based on structural types of rockmass, characteristics of crustal stress, and blasting vibration effect. Kiliç et al. (2009) proposed a model for blastability in terms of tensile strength and coefficient of internal friction. Tsiambaos and Saroglou (2010) proposed a classification method for rockmass excavatability based on GSI but they did not present any formula for the calculations. Split Hopkinson pressure bar tests on artificial joints in blocks were conducted by Li et al. (2016) who observed that the deformation of rockmass is caused by the joint deformation and the closure volume of joints increases when contact area declines. Choudhary et al. (2016) reported the effect of rockmass properties on blast fragmentation and concluded that with increase in porosity, compressive strength, and size of the in situ blocks, the fragment size decreases but increases, if the density of rock increases.

Also, the rockmass, blast design, and explosive properties vary in a mine and results in variation in blast outcomes like fragmentation. If such variables are treated as distributions, the resultants conform to the measured results (Thornton et al., 2002). The method proposed by Thornton et al. (2002) provides a basis for revisiting the existing method of reporting and analysis of blast input, output variables, and related analysis. McKenzie et al. (1982) attempted to quantify rockmass variables for modelling of fragmentation using a cross-hole acoustic method incorporating propagation velocities of waves and their attenuation. Nevertheless, Sellers et al. (2019) concluded that there is no commonly accepted method of rock blastability which should include rockmass strength, fracture frequency, and density. They supported the use of seismic velocities for such classifications as these present a holistic picture of the rockmass.

However, the classification system that defines blastability specifically while using the macroscopic properties of the rockmass was introduced by Lilly (1986). This classification, popular despite its shortcomings, uses a rating for different factors used to define a blastability index (I_{BI}) and is given in Table 1.4.

TABLE 1.4
Ratings Used in Lilly's (1986) Classification System for Defining Blastability Index

Description	**Rating**	**Details**
RMD (rockmass description)	10	Powdery/Friable rockmass
	20	Blocky rockmass
	50	Totally massive rockmass
JPS (joint plan spacing)	10	Close spacing (<0.1 m)
	20	Intermediate (0.1–1.0 m)
	50	Wide spacing (>1.0 m)
JPO (joint plane orientation)	10	Horizontal joints
	20	Dip out of the face
	30	Strike normal to face
	40	Dip into face
SGI = Specific gravity influence	25 × SG – 50	SG is the specific gravity of rock (t/m^3)
H = Hardness	1–10	Mohs scale

The blastability index (I_{BI}) can be calculated by substituting the ratings in Table 1.4 in Equation 1.5:

$$I_{BI} = 0.5 \times \left(RMD + JP + JPO + SGI + H \right) \tag{1.5}$$

The specific charge (q) and the energy factor (E_f) can be worked out from Equations 1.6 and 1.7, respectively.

$$q = 0.004 \times I_{BI} \tag{1.6}$$

$$E_f = 0.015 \times I_{BI} \tag{1.7}$$

The rock constant or factor mentioned in Equation 1.4 can be estimated by modifications in Equation 1.5 and is given in Equation 1.8.

$$I_{BI} = 0.06 \times (RMD + SGI + H) \tag{1.8}$$

Bameri et al. (2021) presented a case study of application of I_{BI} (Lilly) in a copper mine while using Monte Carlo simulation and found that the method provided a better insight into the combinatorics of rockmass factors. The use of I_{BI} in the prediction of fragmentation and wall control is documented in Chung (2001), Chung and Katsabanis (2000), Monjezi et al. (2011), Segaetsho and Zvarivadza (2019), and many other such publications.

TABLE 1.5
Blastability Classification of Rockmass Incorporating Adjustments for Confinement and Stiffness (Ghose, 1988)

Variable	**Range**				
Density, t/m^3	<1.6	1.6–2.0	2.0–2.3	2.3–2.5	>2.5
Rating	20	15	12	6	4
Spacing of discontinuity, m	<0.2	0.2–0.4	0.4–0.6	0.6–2.0	>2
Rating	35	25	20	12	8
Point load strength index, MPa	<1	1–2	2–4	4–6	>6
Rating	25	20	15	8	5
Joint plane orientation	Dip into face	Strike normal to face	Horizontal joints	Dip out of face	Strike at an acute angle to face
Rating	20	15	12	10	6
Adjustment factor, A_{F1}	Highly confined, Reasonably free,	Rating = −5 Rating = 0			
Adjustment factor, A_{F2}	Hole depth to burden ratio Hole depth to burden ratio Hole depth to burden ratio		>2 0, Rating = 0 = 1.5–2.0, Rating = −2 <1.5, Rating = −5		
Blastability Index	70–85	60–70	50–60	40–50	30–40
Specific charge (kg/m^3)	0.2–0.3	0.3–0.5	0.5–0.6	0.6–0.7	0.7–0.8

Lilly's (1986) classification system was further modified by Ghose (1988) by incorporating influence of confinement and stiffness that is defined in terms of hole depth to burden ratio (Equation 1.9):

$$I_{BI} = \rho_r + J_s + I_{PL} + J_{PO} + A_{F1} + A_{F2} \tag{1.9}$$

where ρ_r is the density of rock in t/m^3, J_s is the joint spacing in m, I_{PL} is the point load strength index, J_{PO} is the joint plane orientation, and A_{F1}, A_{F2} are adjustment factors (Table 1.5). The blastability index values and corresponding specific charge can also be seen in Table 1.5.

The classification of Ghose (1988) is an improvisation of Lilly's (1986) original method as it incorporates some design aspects relating to hole depth, burden, and confinement of a blast. Other blastability assessment methods have been compiled in Table 1.6.

Salmi and Sellers (2021) summarized most of the developments in blastability through a comprehensive review that found the dynamic breakage of rockmass influenced by the strength, density, and structure of the discontinuities in the rockmass. They held that in situ block size defines the fragmentation, attenuation of stress waves, and the extent of damage zone about blastholes. They identified a comprehensive list

TABLE 1.6
Few Other Blastability Assessment Methods

S. No.	Citation	Equation	Description
1	Muftuoglu et al. (1991)	$q = 0.0025\sigma_t^2 - 0.0042\sigma_t + 0.1363$	Specific charge (q) in kg/m^3 is defined as second-order equation of tensile strength (σ_t)
2	Scott (2020)	$f_d = 0.0371 \times \rho_r^2 - 0.0512\rho_r + 0.9172$	Density factor (f_d) which is a quadratic function of density (ρ_r) is in T/m^3
3	Borquez (1981)	$c = 1.96 + 0.27 \times \ln(ERQD)$	Blastability factor (c), equivalent rock quality designation (ERQD) that considers joint strength and alteration
4	Da Gama (1995)	$C = 15424c^2 - 2840.6c + 146.27$	Blastability (c), cohesion (C) is in MPa
5	Scott and Onederra (2015)	$f_s = 0.0549 \times \sigma_c^{0.5315}$	Strength factor (f_s) as a function of compressive strength (σ_c) is in MPa
6	Rakishev (1981)	$\sigma_s = 0.1\sigma_c + \sigma_t$	Limit strength of the rocks (σ_s) in MPa is expressed in terms of compressive and tensile strengths
7	Kou and Rustan (1992)	$c = \dfrac{\sigma_c^2}{2E_r \times \eta \times Q_e}$	Blastability factor (c) is given in terms of σ_c, detonation heat (Q_e) in kJ/kg, Young's modulus of rock (E_r) in MPa, and energy transformation efficiency (η)
8	Zou (2016)	$N = 67.22 - 38.44Ln(V_c) + 2.03Ln(\rho_r C_p) + K$	Rock blastability is defined in terms of volume of crater (V_c) in m^3, p-waves velocity (c_p) in m/s, ρr in ×103 kg/m^3, index of rock fragmentation (K)
9	Qu et al. (2002)	$f_e = a_1\rho_e c_d^2$ $c = a_2(\rho_r\sigma_c^{\alpha})\log(a_3 S_{javg})^{\beta}$	Explosive strength factor (f_e), ρ_e in ×103 kg/m^3, constants which can be determined from regression analysis ($a1$, $a2$, $a3$, α, β), velocity of detonation (c_d) in m/s, blastability (c), average joint spacing (S_{javg}) in ×10^{-2} m, σ_c in ×10^{-3} MPa
10	Livingston (1956)	$B_{opt} = k^3\sqrt{Q}$	Optimum breakage burden distance or charge depth (B_{ob}) in m, k is a constant of proportionality expressing rock and explosive properties, Q is the mass of explosive in kg
11	Dick et al. (1990)	$\log\sqrt{(B_{opt}^2 + r_a^2)} = 1.846 + 0.312\log Q$	Optimum breakage burden distance is a function of apparent crater radius (r_a) and the equivalent TNT charge mass (Q)

of almost 32 blastability assessment methods found in the literature and ranked these for establishing a three-dimensional classification system for blastability. However, the universal acceptance of any of the methods, defining blastability, is still lacking.

1.3.3 Explosive and Blast Design

Explosives properties play a major role in defining the outcome of the blast (Božić, 1998). A comprehensive detail of explosives, their use, and some basics related to the outcome of blasts are provided by Cooper (1996). Commercial explosives are mixtures and hence cannot be directly tested efficiently for their energy yield. Fragmentation efficiency is based on ratings that are given by explosive manufacturers through proprietary codes (Djordjevic, 2001). This limits the comparison of results of explosives of different manufacturers. Djordjevic (2001) developed a code named CHEETAH for explosive standardization and concluded that the code can be used further for explosive selection on optimal basis. Owing to the complexity in such calculations of energy, users generally resort to simple assessment of velocity of detonation and density of explosives that yields its impedance and have been correlated for determination of blasthole pressures (Cooper, 1996) as provided in Equation 1.10:

$$P_b = \frac{\rho_e \times c_d^2}{8} \tag{1.10}$$

where P_b is the blasthole pressure, $\times 10^3$ MPa, and is generally considered to be 0.5 times the detonation pressure; ρ_e is the density of explosive, kg/m^3; and c_d is the velocity of detonation of explosive, m/s.

As mentioned earlier, the best way of selection of explosive is to match the impedance of rock with that of the explosive. There is a further scope of improvement in Equation 1.10 since density and velocity of detonation of explosive are related significantly (Cunningham, 2006).

Trials in blocks of granite, porous limestone, and sandstone with different explosives were conducted by Bergmann et al. (1973) and they correlated energetics of explosive with average fragment size, burden velocities, and peak pressures. Bergmann et al. (1973) derived that the fragmentation is controlled by explosive energy, its detonation velocity and density, and the degree of coupling, a ratio of explosive diameter to blasthole diameter. Although the study was conducted on blocks and may not reflect the impact of joints, the study provides a basis for determination of such relationships and need to be extended to full-scale blasting in actual bench conditions. However, such conclusions were contested by Cunningham (2006) citing that the results were due to the size of blocks and not due to the velocity of detonation. Later, Agrawal and Mishra (2017) found that the velocity of detonation of an explosive, under specific rock and test conditions, can be used to evaluate the performance of the explosive used in mines.

A method to determine the pressure fluctuations adjacent to the blasthole due to gas was developed by Williamson and Armstrong (1986). The authors claim that the

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