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Prof. Sanjay Kumar Sharma	**Dr. Nawal Kishore**
(Supervisor & Chairman)	(Co-supervisor)
Department of Mining Engineering	Department of Mining Engineering
IIT BHU, Varanasi- 221005	IIT BHU, Varanasi- 221005

DECLARATION

I, *ANAND KUMAR*, certify that the work embodied in this thesis is my own bona fide work and carried out by me under the supervision of ***Prof. SANJAY K. SHARMA*** *and co-supervision of* ***Dr. NAWAL KISHORE*** from *JULY 2014* to *DECEMBER 2021*, at the *DEPARTMENT OF MINING ENGINEERING*, Indian Institute of Technology, Varanasi. The matter embodied in this thesis has not been submitted for the award of any other degree/diploma. I declare that I have faithfully acknowledged and given credits to the research workers wherever their works have been cited in my work in this thesis. I further declare that I have not willfully copied any other's work, paragraphs, text, data, results, *etc*., reported in journals, books, magazines, reports dissertations, theses, *etc*., or available at websites and have not included them in this thesis and have not cited as my own work.

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Signature:	Signature:
Prof. Sanjay Kumar Sharma (Supervisor) Department of Mining Engineering IIT (BHU) Varanasi-221005	Dr. Nawal Kishore (Co-supervisor) Department of Mining Engineering IIT (BHU) Varanasi-221005

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Dedicated to my Mom
&
My Family

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LIST OF ABBREVIATION

Symbol	**Title**
A, k, b, n, α, and β	Site-specific constants
A_0	Initial amplitude of seismic wave
A	Amplitude of seismic wave
ANFO	Ammonium nitrate and fuel oil
ANN	Artificial neural network
B	Burden
BIGV	Blast-induced ground vibrations
BPANN	Back-propagation artificial neural network
D	Distance
DGMS	Directorate General of Mines Safety
DIN	German standard
F	Frequency
FIM	Finite element method
HD	Hole depth
HDI	Hole diameter
HSD	High speed diesel
IS	Indian Standard
LRA	Linear regression analysis
MCPR and Q_{max}	Maximum charge per delay
MVRA	Multivariate regression analysis
NH	Number of holes
OSMRE	Office of Surface Mining Reclamation and Enforcement
PF	Powder factor
PPV	Peak particle velocity
PVS	Peak vector sum
Q	Quality factor
R	Radial velocity
RMSE	Root mean squared error
SD	Scaled distance
SSE	Summed squared error
S	Spacing
SVM	Support vector machine
T	Transverse velocity
TB	Total booster
TC	Total charge
TL	Trunk line
TY	Total yield
USBM	United States Bureau of Mines
VOD	Velocity of detonation
V	Vertical velocity

ABSTRACT

Blasting was path breaking advancement in technology over its earlier options of rock-excavations. Even today, blasting technique as adopted in mining and civil engineering continues to be the cheapest means of rock excavations across the world. In India, it is deployed over 90% of the rock excavations. Almost 100% extraction of ornamental rocks, construction materials, and many ore deposits from different mines are from the surface mines. Despite significant advancements in blasting operation and techniques, effective utilization of explosive energy is still lacks perfection. In rock blasting, only 20-30 % of the energy produced by explosives is utilized in fragmentation and displacing of the rock mass. The rest of the energy is wasted producing undesirable environmental impacts like ground vibrations, air overpressure (AOP), fly rocks, and back-breaks. The blast induced ground vibrations is one of the major issues associated with blasting. They are an inescapable occurrence in the vicinity of mines and quarries. It at the least creates human discomfort to people of surrounding areas. Further, cosmetic to large scale damage to the nearby structures, and other environmental damages are also attributed to it. The intensity of these ground vibrations depends mainly on the uncontrollable (geology, physical properties of rock, etc.) and controllable parameters (burden, spacing, maximum charge per delay, blast-hole dimension, bench height, delay operator, etc.). Therefore, challenge lies in predicting and assessing the magnitude of the blast induced ground vibrations and its associated frequency, near the residential structures close to operating mines and quarries. Complexities abound due to insufficient data for the physical properties of the rock mass, the difficulty in accurate identification of the sources of vibrations and the resulting near and far-field behavior. Nevertheless, in spite of these obstacles, it is possible to make realistic assessments of the propagating waves using available empirical and numerical methods. Globally, various researchers have developed the different vibration attenuation equations on the basis of the

maximum charge per delay and the monitoring distance from the blast site to predict the PPV. However, the ground vibration is affected by many other factors like geology, physical properties of the rock mass, presence and distribution of discontinuities and their characteristics, blast design, bench geometry, etc. Efforts were also made to develop standard damage criteria for safe level of different structures according to the regional conditions. These criteria are based on PPV and its associated frequency. Various mathematical tools like ANN, FIS, SVM, ANN-PSO, Fuzzy Logy, PCA, MVRA, etc. have been deployed to predict the peak particle velocity (PPV) and the frequency for the appropriate prediction of the blast-induced ground vibrations.

In this study, the monitoring of ground vibration was conducted through peak particle velocity and the associated frequency and their orthogonal components with peak vector sum PVS using seismographs. During the study, the data acquisition of the blasting parameters, blast geometry, monitoring distance from the blast site from five different mine and quarry comprising of two opencast coal mines, one open-pit limestone mine, and two stone quarries. These datasets were processed through different applied models such as empirical attenuation model, multivariate regression analysis (MVRA), and back propagation artificial neural network (BPANN) approach to predict PPV and frequency. Finally, the predicted values of these different models were compared with the measured values and the correlation coefficients between the measured and the predicted values were also assessed.

Many studies on the impact of the blast induced ground vibrations have been conducted on rocks of different nature and formations. This study intentionally attempted to assess the damage associated with variations in the rock types and success of predictor equations under different geo-mining conditions for BIGV.

During blasting operations, several negative impacts like ground vibrations, air overpressure, fly rocks, dust cloud of fine particles, and huge noise is produced. Of these, the blast induced ground vibrations is the most severe impact as it not only discomforts people but also damages the structures nearby the mines and quarries.

Blast induced ground vibrations cause short durational and long durational impact as enlisted below:

Short durational impacts of ground vibrations:

- Impact on the nearby structures
- Impact on the people
- Environmental impacts

Long durational impacts of ground vibrations:

- Impact on the nearby structures
- Gradual destabilization of the overburden dumps, if any
- Impact on mine haul roads
- Impact on the surface water (migration)
- Impact on ground water (migration)
- Impact on aquifers and reservoirs

During blast induced ground vibrations, duration of vibrations, number of the repetitions, and repetition rate of ground vibrations directly contribute to the probability of the damages. The structures develop hairline to major cracks on the surface or even severe structural damage due to such blast induced ground vibrations. The problems associated with the blast induced ground vibrations need precise and accurate identification and possible solutions in the field through continuous monitoring and analysis. For minimizing these damages, suitable blast design, explosives, and blasting accessories needs to be selected.

The objectives for the present study are:

- To qualitatively assess the impacts of BIGV on nearby structures.
- To establish limits of the zones of destractruction for maximum charge per delay.
- To obtain the safe charge weight per delay for different distances under observation.
- Comparative analysis of the performance and suitability of predctor models, BPANN, and MVRA techniques.
- To determine the site constants for in-situ rock mass.

The research methodology comprised of literature review, field survey, and recording of the data of various parameters of ground vibrations in different mines and quarries, and the analysis of the data from the experimental blasts. These data were processed and analysed through the various models like linear regression analysis, empirical attenuation models, multivariate regression analysis, and back propagation artificial neural network. In order to identify the impacts of the blast induced ground vibrations and minimise the risk of damages to the structures, efforts were made to assess and predict the peak particle velocity and the dominant frequency. The predicted values were compared with the measured values to evaluate the correlation between them.

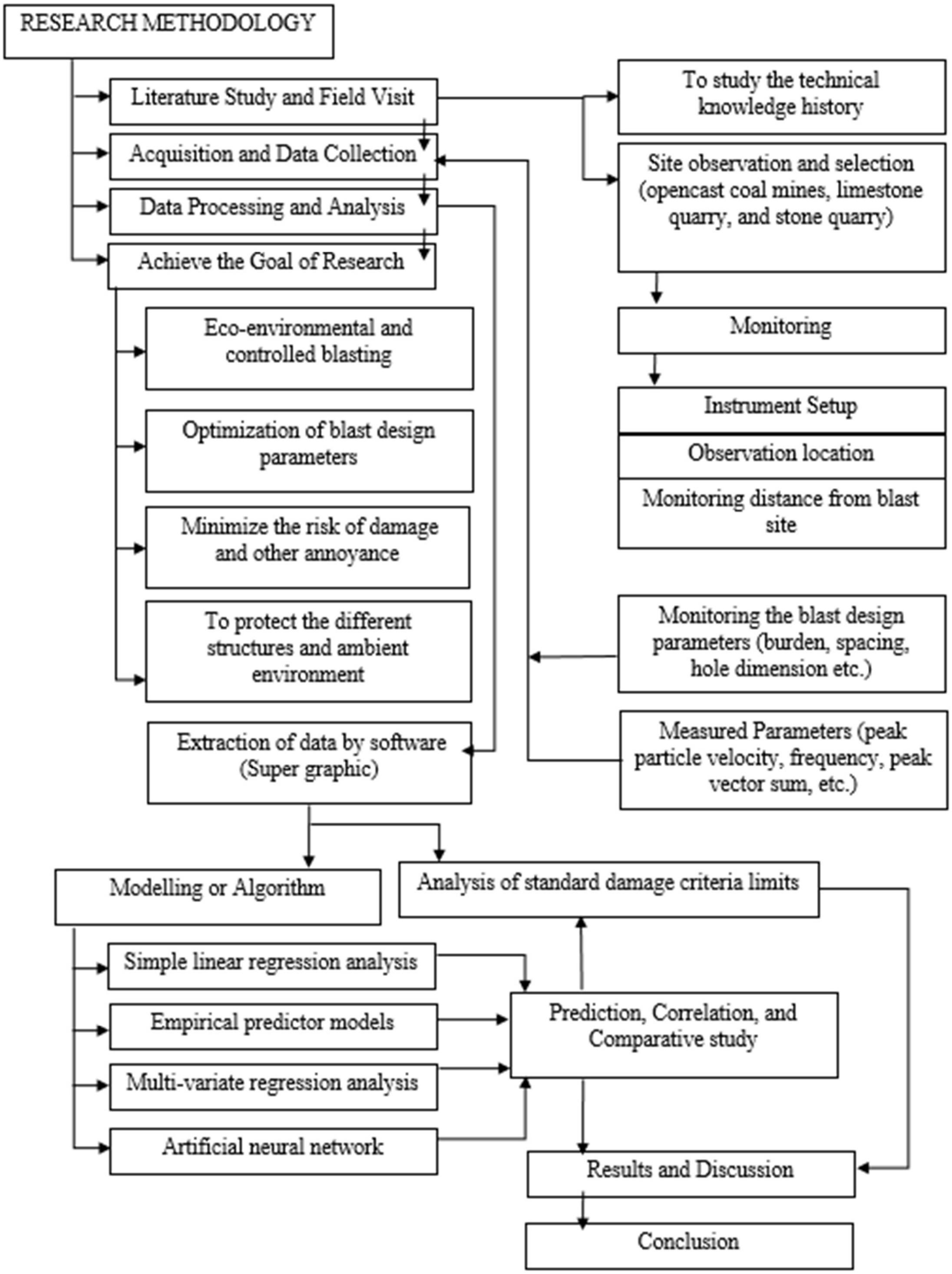

Fig.1. The flow chart of research methodology.

On the basis of the field experiments and the analysis, the research contributions are significant in:

- Development of methodologies for the estimation of safe charge weight per delay in the selected mines and and quarries.
- Development of methodologies to identify the significant parameters of blast-induced ground vibrations.
- Qualitative and quantitative assessment of the damage level of different structures due to blasting.

Based on the current work, following conclusions have been drawn:

- The structures are continuously accumulating stress-energy of the blast-induced ground vibrations. The stress-energy is released in the form of strain along the weakest section of structures resulting in the progressive development of cracks.
- A-H, D-P/GP, IS/L-K BIGV attenuation models gave completely different values of safe charge per delay with increasing distance.
- The backpropagation ANN, and MVRA predicted BIGV PPV and the dominant frequency with accuracy over the attenuation models.
- The correlation coefficient between measured and predicted PPV was 92%, 75%, 72% by ANN, MVRA, IS, respectively.

The major outcomes of this research work are as follows:

- Continuous monitoring and accurate prediction of the blast-induced ground vibration by ANN and MVRA models.
- Estimation of the safe charge weight per delay for the numerous blast events studied.
- Establishment of the correlation between damages to structures and intensity of the blast-induced ground vibrations at different distances.