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Prediction of blast-induced ground vibration using multi-variate regression analysis in an opencast mine

The consumption of hydrocarbon is increasing day by day. A number of technologies are being used to meet out the demanded quality. The drilling and blasting is a cheapest way to exploration and excavation in mining industries. The blasting creates excessive amount of energy in different form of ground vibration as shaking of Earth, flyrock, removal and transportation of overburden rockmass and other noise. Blast-induced ground vibration has some adverse effects on surrounding environment as well as community living nearby the opencast mine. The study was conducted at opencast coal mine in Chhattisgarh. A total number of 32 data sets have been measured with different parameters such as; maximum charge per delay (MCPD), observation distance, charge length, spacing, burden, blast hole depth, hole diameter, etc. as well as peak particle velocity (PPV), frequency and peak vector sum (PVS). In present study, main focus on measurement and prediction of peak particle velocity by different predictor model (USBM, Indian Standard, DGMS) and multi-variate statistical regression analysis (MVSRA). Simple linear regression model (SLRM) is used to determine the site characteristics constants. The constants are used to establish new prediction model equations among different parameters. Finally, assess the blast induced ground vibration on the basis of measured and predicted peak particle velocity.

Keywords: *Blasting, ground vibration, PPV, maximum charge per delay, MVSRA*

1.0 Introduction

The natural energy resources are the essential minerals having an important place in human life. The hydrocarbon are conserved in Earth's interior in different form like coal, oil and gas. The exploration and excavation of the hydrocarbon tend to increase day by day due to increasing the demand and production. Therefore, the different types of approaches are being made to fulfill their requirements. The blasting technique is frequently applied in an opencast mine for excavation of coal, removal and breaking of overburden rockmass, in which tiny to massive amount of explosives are being used.

Drilling and blasting are the principal techniques of excavation in India and its contribution about 90% in coal extraction and 100% in metalliferous ore deposit. The quantity of explosives and its fire depends mainly upon the blast design parameters. The small portion of energy (20-30%) released on firing of explosives utilized for desirable action (i.e. braking and removal of rockmass) and rest of energy goes into ground and air, known as unwanted energy [1]. The waste energy is dissipated into subsurface in the form of ground vibration as wave energy, noise, heat energy and in air as airover pressure, fly rock, etc. The blast-induced ground vibration is due to movement of large fraction of waste energy. Sometimes, it crosses permissible level and cause damages to natural and man-made structures, and harmful for human comfort [2]. Blast-induced ground vibration is an integrated result of body wave (primary wave secondary wave) and surface wave (rayleigh wave); called seismic wave and it is propagation into ground is as shown in Fig.1. The longitudinal (or radial), transverse and vertical velocities are the components of peak particle velocity, the maximum value among three velocities is known as PPV. It varies with monitoring distance from source, amount of explosive, and anisotropic behavior of rockmass[3]. PPV provides the quantitative values of intensity of blast-induced ground vibration at every blast, well-known relationship (1).

$$PPV = k(D/\sqrt{Q})^{-b} \quad \text{... (1)}$$

Value within a bracket of equation (1) is called scale distance SD. Where D(m) – observation distance between

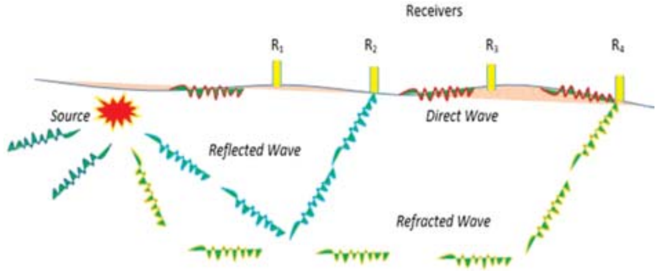

Fig.1: The wave propagation into ground from source to receivers

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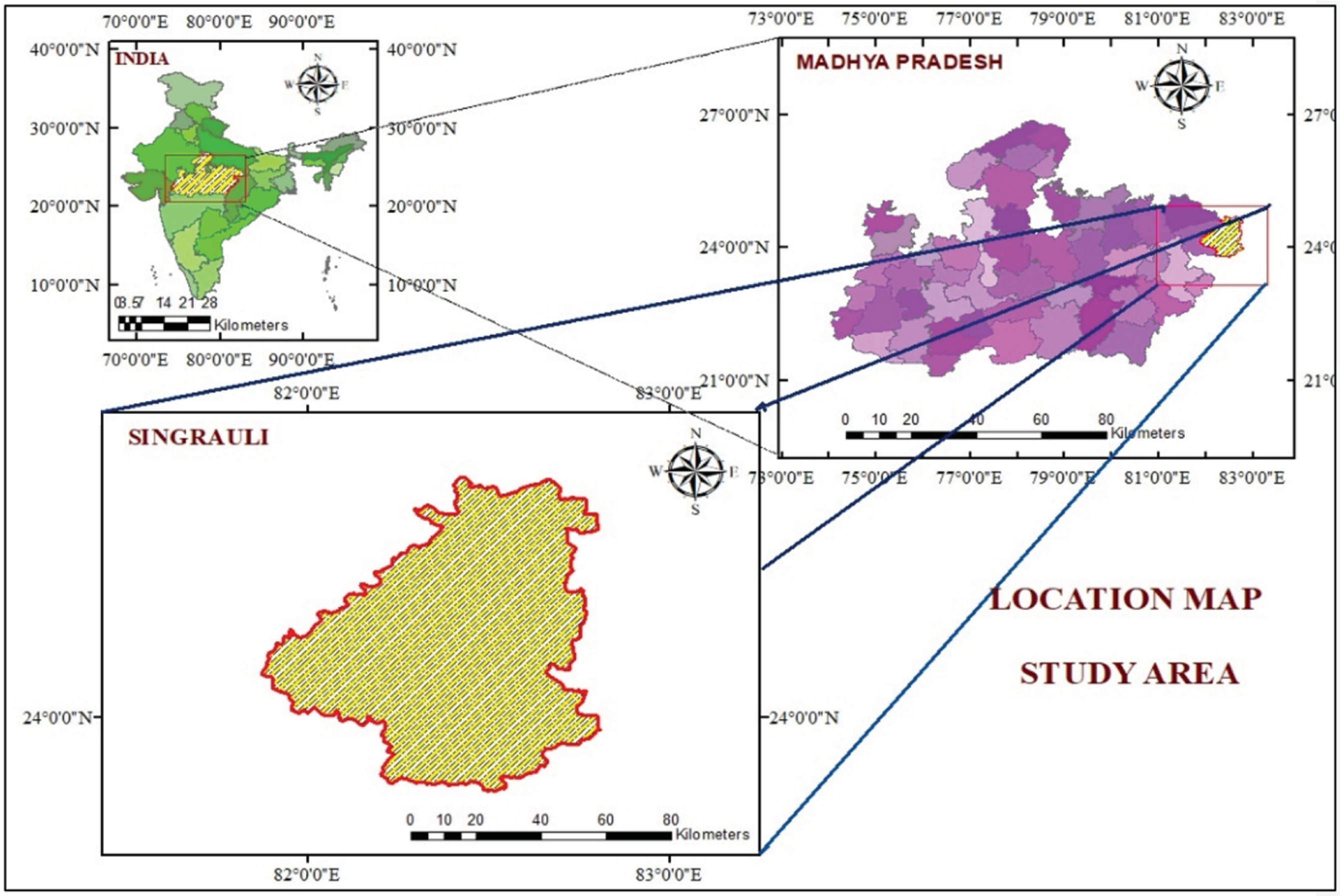

Fig.2: Location map of study area

blasting site and measuring point, Q(kg) – maximum charge per delay, k, and b are the site-specific constants, determined by regression analysis. PPV is a dependent variable parameter depends on the independent variable parameters such as; physical properties of rockmass which change from one place to another or heterogeneity, geological condition, blast design, discontinuity, nature of wave propagation and distance from shot point to measuring point [4-5]. The peak particle velocity, frequency, and vector sum play a vital role to assess, control and monitoring the seismic hazard, structural damage and human discomfort caused by blast-induced ground vibration. They decide or make the seismic hazard zone near mine for public safety purpose and help to prevent danger. Frequency-dependent peak particle velocity give more reliable results for the assessment of vibration because every structures have their natural frequency [6]. Vector sum is defined as the square root of sum of square of component velocities (longitudinal, transverse and vertical), as equation (2).

$$VS = \sqrt{R^2 + T^2 + V^2} \quad \text{... (2)}$$

Various scientists and engineers developed many vibration predictor models for prediction of PPV [7-13]. All the models are dependent only on two variables like maximum charge and distance between the blast site and observation station. Some of them used attenuation coefficient as exponential order. Different model equations give different values of safe PPV with regard to charge per delay. All the model equations do not provide the same result of PPV at the same mine site because their PPV depends not only above two variables but also on blast design, geological and geotechnical condition and explosive's parameters. The models are not able to predict any other vital factors like frequency, airover pressure, etc. These predictor models are equally effective for safe, easy and ecofriendly excavation of overburden rockmass for mining and other projects. Frequency-dependent PPV give critical result for safe and smooth excavation [6].

2.0 Study area and geology

The study was conducted in an opencast coal mine (lies between latitude 22°19'14.988"N and longitude 82°31'30.67"N) located in Chhattisgarh as shown in Fig.2. Granite, dolerite, bauxite, fireclay, and limestone deposits are also found in this area. The overburden rockmass is of medium to coarse grain sandstone, shale, shaly sandstone, and mostly weathered sandstone, etc. The mine has mostly bituminous coal of Gondwana age [14-15]. Different samples like weathered rock, block of sandstone and coal, and overburden rockmass strata as shown in Figs.3, 4, 5 and 6, respectively.

Fig.3: Sample of weathered sandstone

Fig.4: Sample of coarse grain sandstone

Fig.5: The samples of coal

Fig.6: Sample of overburden strata

Fig.7: The survey along with white line

3. Field procedure equipment and data acquisition

In field, a simple procedure is applied due to irregular or complex nature of mine. First, a survey line is made from the blasting site at the mine to last observation point near the village (1.4 km-1.5 km long), as shown in Fig.7. The ground vibration is measured in the form of PPV and their components by using four seismographs (Nomis; which has tri-axial geophone) and other one Instantel. The tri-axial geophone and microphone associated with seismograph are set in field. The seismographs with geophone have been located at every 100m interval but data monitored at every 50m interval as shown in Fig.8. A total number of 32 data sets have been measured by the eightblast event in some days and are listed in Table 1. Blast design parameters and materials ranges such as blast hole depth (3.5m-20m), blast hole diameter (16mm-381mm) as shown in Fig.9, burden (3.5m- 8m), spacing (3.0m-8.5m), charge per hole (19.1kg-560kg), bench height (3.0m-20m), booster per hole (100g-1200g) and staggered pattern have been used. The delay operators as 17ms, 42ms are used in line and cross line respectively, along with DTH delay 200ms - 250ms as shown in Fig.10 [16].

Fig.8: Installed seismograph with geophone

Fig.9: Blasthole sample

Fig.10: Delay operator

4.0 Blast-induced ground vibration analysis and mathematical approaches

The blast-induced ground vibration has been measured between blasting site and observation point near villages, seismograph are installed at 50m, 100m, 150m, up to 1400m. Nomis seismographs has been used, which has tri-axial geophone that measures three components (R, T, V) of PPV at their own frequencies. The maximum value of these components (R, T, V) is defined as the main PPV value. Data have been analyzed through some mathematical operation SLRA, MVRA and empirical model and software of Nomis and excel. Nomis software is beneficial in the study of PPV, frequency, components (R, T, V) of PPV and some other parameters and plot various graphs such as; USBM RI 8507, IS(DGMS) and DIN 4150, etc. In last five decades, Scientists and engineers described the attenuation characteristics of induced vibration with the help of their predictor equations of PPV [17-19]. Here, the United States Bureau of Mines (USBM) and Indian Standard (DGMS) predictor model equation have been used as given in Table 1.

4.1 General Empirical Model Equation

$$PPV = k\,(SD)^{-b} \qquad \text{... (3)}$$

$$\log PPV = \log k + (-b)\log SD \qquad \text{... (4)}$$

Where, k and b are the site characteristics constant of rockmass in equation (3). SD is scale distance which depends on two parameters distance (D) between source and receiver and maximum charge per delay (Q). But different researchers have used different scale distance SD in their models such as;

4.1.1 Duvall and Petkof (USBM) model

SD = D/”Q

$$PPV = 474.63(SD)^{-1.5016} \qquad \text{... (5)}$$

4.1.2 Indian standard (DGMS) model

$$SD = D/Q^{2/3} \text{ and } PPV = 175.790(SD)^{-1.6256} \qquad \text{... (6)}$$

4.2 Simple Linear Regression Analysis (SLRA)

Regression analysis is a powerful statistical method that examines the relationship between two or more independent variables. Equation (4) looks like equation (7) of a straight line.

$$y = \beta_0 + \beta X \qquad \text{... (7)}$$

$y = \log PPV$, $\beta_0 = \log k$, $\beta = (-b)$, and $X = \log SD$

SLRA is an appropriate mathematical operation to determine the slope and intercept of the equation of straight line, as site constant. The values of site characteristic constant (k, b) of rockmass are described in the above equation (5), (6) by Duvall and Petkof (USBM), and Indian Standard (DGMS), respectively.

4.3 Multi-variable Regression Analysis (MVRA)

When the dependent variable depends on more than one independent variable called multi-variable regression analysis (MVRA) which gives its correlation. The general relationship is as given under.

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_5 X_5 + \dots + \beta_n X_n + E \qquad \text{...(8)}$$

Where, β_0–interceptand $\beta_1, \beta_2, \beta_3, \beta_4, \beta_5, \beta_n$ are the coefficient or slope of the independent variables X_1, X_2, X_3, X_4, X_5, … X_n, respectively, and error E. Using the MVRA establish the new relationship among the PPV (dependent variable) and independent variables such as; total charge, distance, burden, spacing, number of holes, hole depth, hole diameter and total booster.

5. Result and discussion

The empirical model equation is based on two basic parameters, distance and maximum charge per delay while the ground vibration depends on many parameters. In such cases, conventional method may not give appropriate results for PPV. Even through, the conventional method has place in-ground vibration study. USBM and IS (DGMS) have been applied along with SLRA and MVRA. In this study, a number of 32 data sets with different parameters have been measured by four seismographs at an opencast coal mine as listed in Table 1. It has been observed that seismic wave energy decreases with increasing distance from source. Thus, the magnitude of PPV is inversely proportional to distance (D) power of integer (m).

$$PPV \propto 1/D^m \qquad \text{... (9)}$$

‘m’ is an integer that depends upon the characteristics of rockmass and behavior of waves. The measured PPV data sets are used to analyze through SLRA and MVRA, along with the other input parameters, and determine the following relationships:

$$PPV = 474.63(SD)^{-1.5016} \qquad \text{... (10)}$$

$$PPV = 175.790(SD)^{-1.6256} \qquad \text{... (11)}$$

$$\begin{aligned} PPV = {} & 23.16099 + 0.001437\{TC\ (kg)\} \\ & - 0.00868\{D\ (m)\} - 1.87925\{B\ (m)\} + 0.892812\{S(m)\} \\ & - 0.19109\{NH\ (cont.)\} - 0.97733\{HD\ (m)\} \\ & + 0.15876\{HDI\ (mm)\} - 0.06768\{TB\ (kg)\} \qquad \text{... (12)} \end{aligned}$$

Where, TC-total charge (kg), D-distance(m), B- burden(m), S-spacing(m), NH- No. of holes (cont.), HD- hole depth (m), HDI- hole diameter (mm), TB-total booster (kg), and MCPD-maximum charge per delay (kg). These equations (10), (11), (12) gave the predicted values for PPV and found out the correlation with measured PPV values. To obtained correlation coefficient between predicted PPV and measured PPV through the USBM, Indian Standard (DGMS), and MVRA models are 81%, 79%, and 91%, respectively. The regression plots of all models are as shown in Fig.11, 12 and 13, respectively. Multi-variate regression analysis give a better correlation coefficient than the other two. It depends on two or more than two input parameters. All models help to optimization of blast design parameters for safe blasting and

Table 1: Predicted peak particle velocity

	D (m)	MCPD (kg)	TC (kg)	TB (kg)	B(m)	S (m)	NH	HD (m)	HDI (mm)	Measured frequency (Hz)	Measured PPV(mm/s)	Predicted by USBM PPV (mm/s)	Predicted by Indian standard (DGMS) PPV (mm/s)	Predicted by MVRA PPV(mm/s)
1	100	85.76	2230	5.2	4	4.5	52	6.3	160	25.6	9.525	13.48	11.706	8.092
2	200	85.76	2230	5.2	4	4.5	52	6.3	160	22.2	6.096	4.768	3.795	7.229
3	300	85.76	2230	5.2	4	4.5	52	6.3	160	6.1	3.81	2.595	1.963	5.356
4	50	118.7	1840	3.1	4	5	31	6.8	159	23.24	19.609	48.683	51.170	15.062
5	150	118.7	1840	3.1	4	5	31	6.8	159	11.6	11.049	9.369	8.584	11.194
6	250	118.7	1840	3.1	4	5	31	6.8	159	6	4.191	4.354	3.742	5.457
7	350	371	8880	21	8	8.5	28	18.5	259	3.8	5.334	6.179	7.354	4.697
8	450	371	8880	21	8	8.5	28	18.5	259	6.45	4.081	4.238	4.888	3.829
9	550	371	8880	21	8	8.5	28	18.5	259	5.3	3.683	3.136	3.528	2.961
10	650	371	8880	21	8	8.5	28	18.5	259	3.3	2.413	2.441	2.689	2.093
11	400	324.1	7780	18	8	9	24	19	381	8	6.604	4.570	5.120	5.545
12	500	324.1	7780	18	8	9	24	19	381	4.3	4.064	3.270	3.563	4.677
13	600	324.1	7780	18	8	9	24	19	381	2.8	2.54	2.487	2.649	3.809
14	700	324.1	7780	18	8	9	24	19	381	0.8	1.778	1.974	2.062	2.941
15	325	102.8	3600	10.5	5	6	70	7	160	6.3	3.429	2.637	2.094	3.085
16	525	102.8	3600	10.5	5	6	70	7	160	1.982	0.895	1.287	0.960	1.349
17	725	102.8	3600	10.5	5	6	70	7	160	1.045	0.197	0.791	0.568	0.386
18	650	475	8550	21	6	7.5	18	19	260	5.2	4.826	2.938	3.505	5.923
19	750	475	8550	21	6	7.5	18	19	260	128	3.556	2.370	2.778	5.055
20	1150	475	8550	21	6	7.5	18	19	260	4.51	1.905	1.248	1.386	1.583
21	1250	475	8550	21	6	7.5	18	19	260	5.3	1.016	1.101	1.211	0.715
22	800	221.84	4160	7.5	3	4	75	6.5	159	2.147	1.27	1.215	1.105	1.460
23	900	221.84	4160	7.5	3	4	75	6.5	159	3.93	0.762	1.018	0.913	0.592
24	1000	221.84	4160	7.5	3	4	75	6.5	159	2.457	0.335	0.870	0.769	0.275
25	850	470	6580	16.5	6	7.5	14	19.5	381	11.6	4.318	1.949	2.241	3.857
26	950	470	6580	16.5	6	7.5	14	19.5	381	6.3	3.048	1.650	1.870	2.989
27	1100	470	6580	16.5	6	7.5	14	19.5	381	3.9	2.159	1.324	1.474	1.687
28	1200	470	6580	16.5	6	7.5	14	19.5	381	7.1	1.524	1.162	1.279	0.819
29	1050	390	8840	23.4	7	8	26	18	259	7.3	1.143	1.234	1.301	2.642
30	1300	390	8840	23.4	7	8	26	18	259	8.3	0.889	0.896	0.919	0.472
31	1350	390	8840	23.4	7	8	26	18	259	20.4	0.635	0.846	0.865	0.0385
32	1400	390	8840	23.4	7	8	26	18	259	3.48	0.547	0.801	0.815	0.395

safe environment. The measured and predicted peak particle velocity of applied models flow with a number of data sets. The signature of multi-variate regression analysis is very close to measure than the other two as is shown in Fig.14.

5.1 USBM LIMITS

In this study, software plays a vital role in the visual interpretation of blast-induced ground vibration to identify the hazards. A relationship among radial, transverse, and vertical velocity at their corresponding frequencies at different distance. According to the USBM limits RI 8507 model. The characteristics of red line that is connecting a rhombus such as; line connecting upper portion of rhombus describes the damage criteria of industrial or concrete structures, while line connecting lower portion of rhombus describes the damage criteria of domestic structures (i.e. Kuchcha, Brick mortal, etc.). Resultant measured component velocity 9.5 mm/s at corresponding frequency 25.6 Hz at observation point 100m at fixed maximum charge per delay. The velocity could not exceed the upper portion of line but exceed the lower portion. It means industrial structures possibly not damage but accumulate stress energy while the domestic structures possibly undergoe damage as shown in Fig.12.

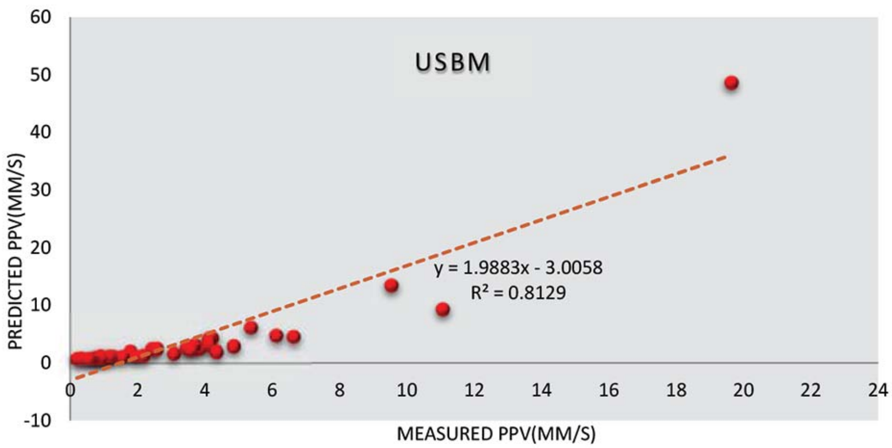

Fig.11. Measured and predicted PPV plot of USBM

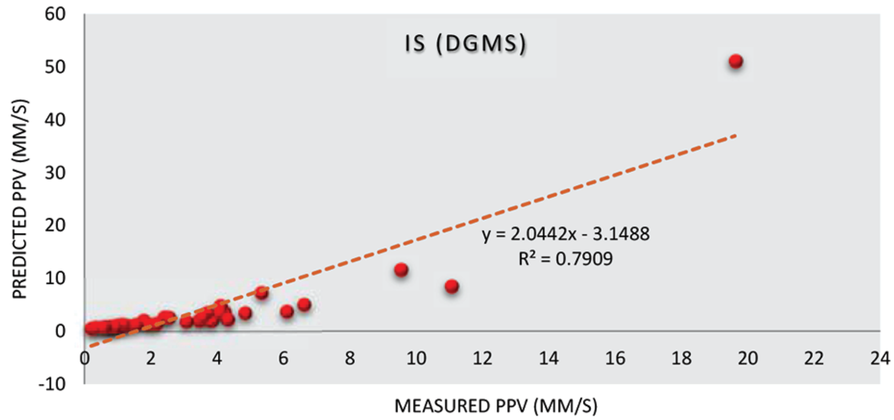

Fig.12 Measured and predicted PPV plot of DGMS

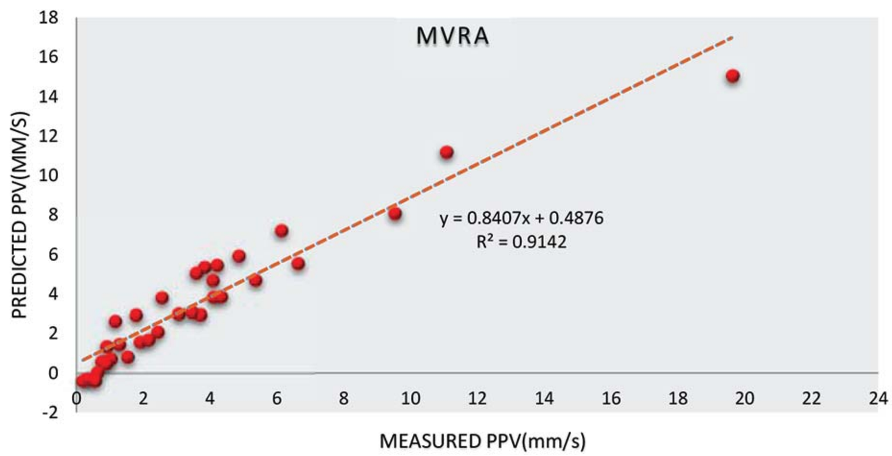

Fig.13 Measured and predicted PPV plot of MVRA

Fig.13 Resultant component (R, T, V) velocity 3.6mm/s at corresponding frequency 5.30Hz. It means industrial and domestic structures should be safe at distance 550m. Figs.14 and 15 resultant component (R, T, V) velocities 0.762 mm/s and 0.635 mm/s at frequencies 3.90 Hz and 20.4 Hz at 900m and 1350m distance, respectively. In both cases, resultant velocity (<1mm/s) is too low it means the effect is negligible on any types of structures.

5.2 INDIAN STANDARD DGMS LIMITS

Indian Standard limits describe the damage criteria by three individual lines (i.e. blue, red, and black). Blue line describes the permissible limit of strong structures like industrial or commercial building and red line for the medium structures like domestic or non-commercial residential building (i.e. Kuchcha, brick mortal houses) and black line describes permissible limit for the weak or old structures (i.e. historical object).

Resultant measured component velocity 9.5 mm/s at

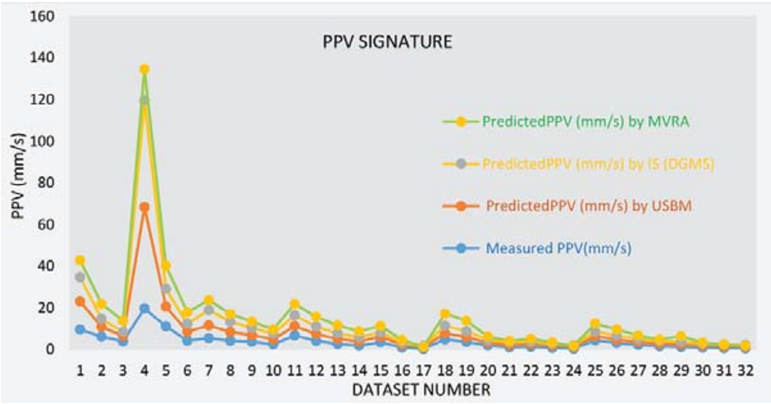

Fig.14: Measured and predicted PPV flow with dataset

corresponding frequency 25.6 Hz at observation point 100m at fixed maximum charge per delay. The velocity could not exceed the blue line but exceed other two lines. It means industrial structures possibly not damage but accumulate stress energy while the domestic and historical structures possibly undergoes damage as shown in Fig.16.

In Fig.17, resultant component (R, T, V) velocity 3.6 mm/s at corresponding frequency 5.30Hz. It means industrial and domestic structures should be safe while historical may damage or not at distance 550m. In Figs. 18 and 19, resultant component (R, T, V) velocities 0.762 mm/s and 0.635mm/s at

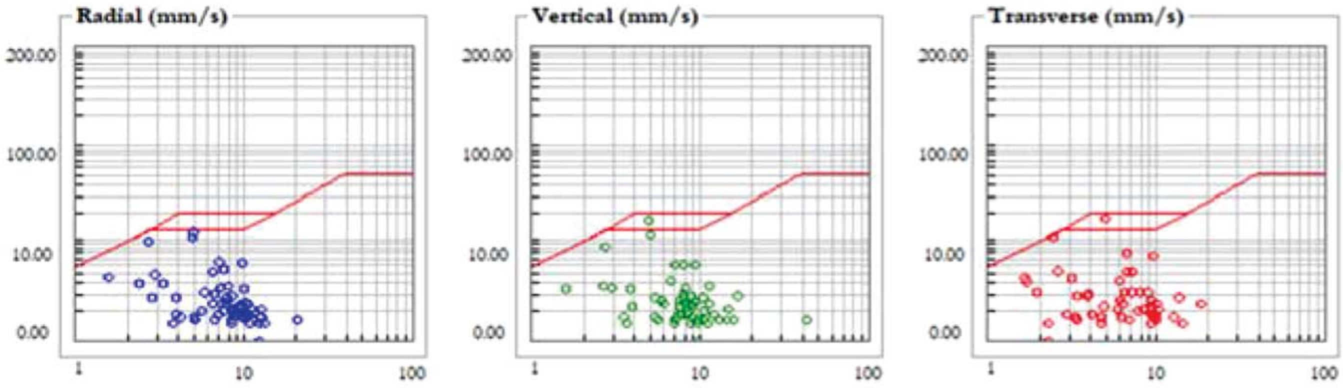

Fig.15: Frequency vs. amplitude plot at distance 100m

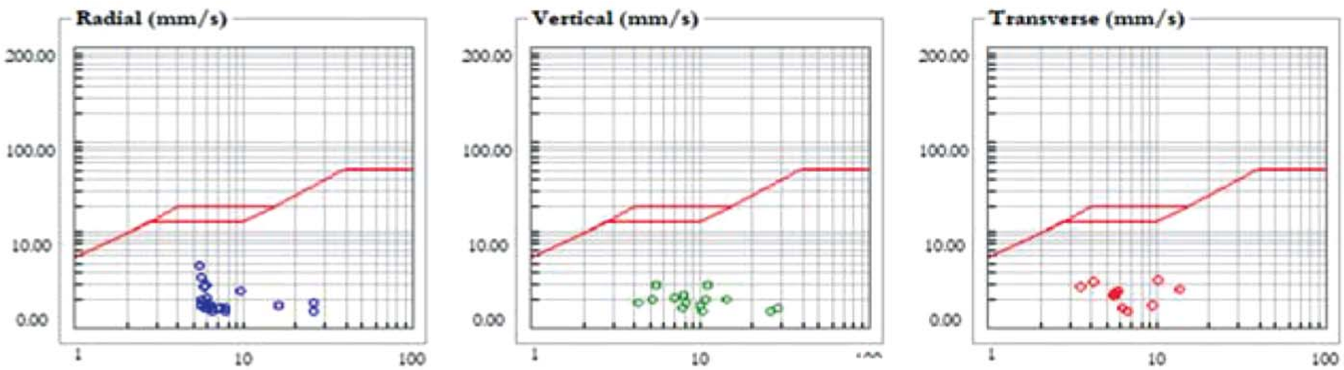

Fig.16: Frequency vs. amplitude plot at distance 550m

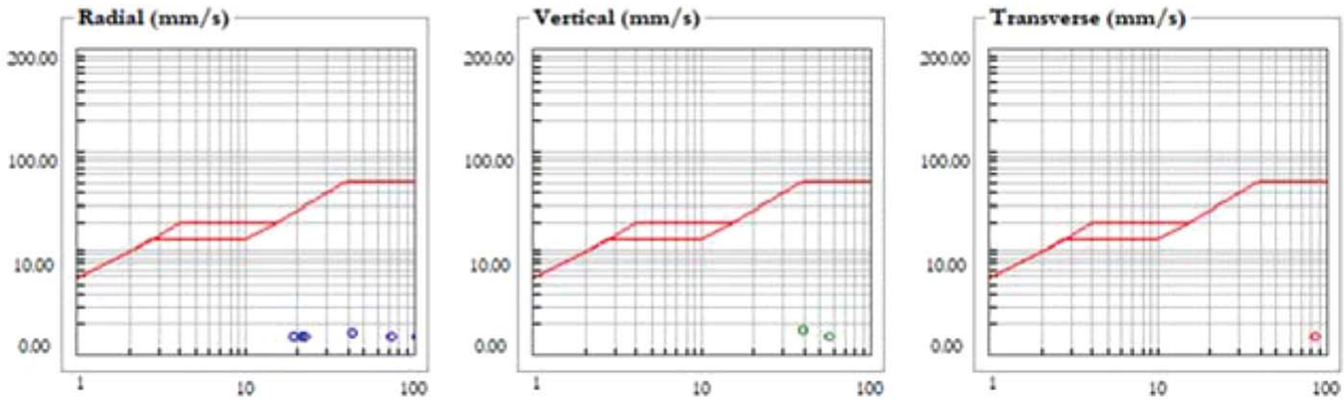

Fig.17: Frequency vs. amplitude plot at distance 900m

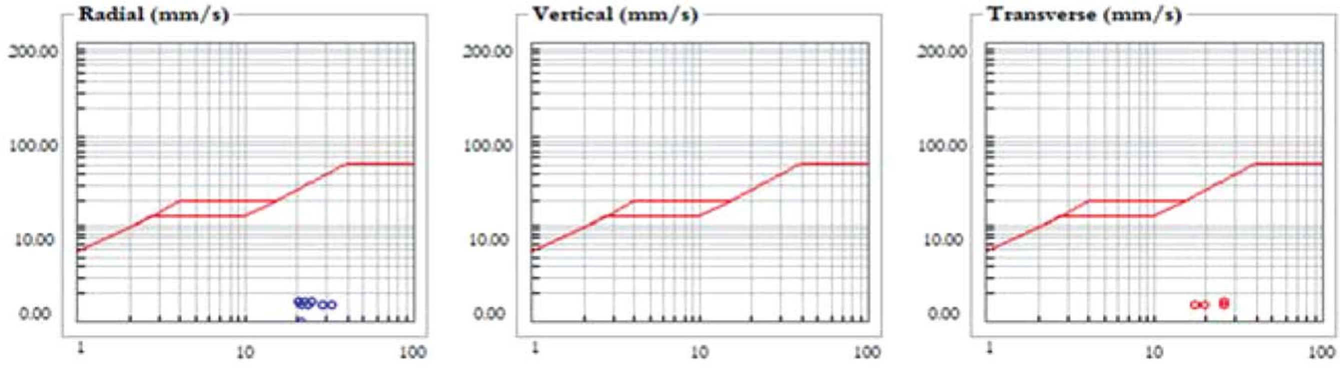

Fig.18: Frequency vs. amplitude plot at distance 1350m

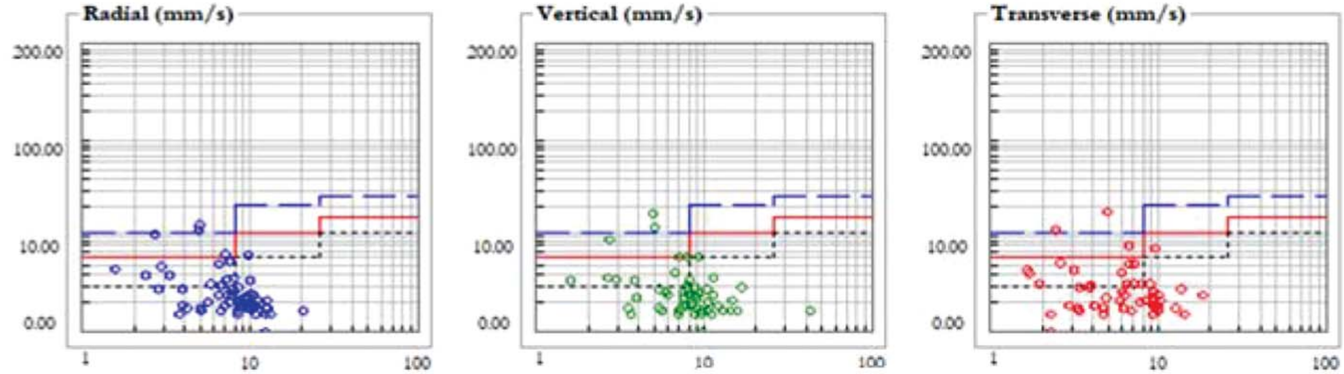

Fig.19: Frequency vs. amplitude plot at distance 100m

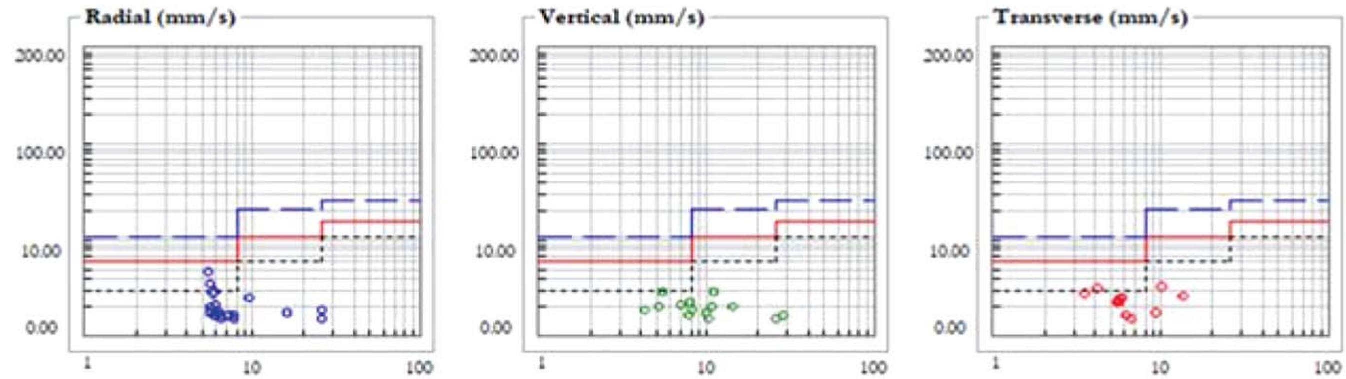

Fig.20: Frequency vs. amplitude plot at distance 550m

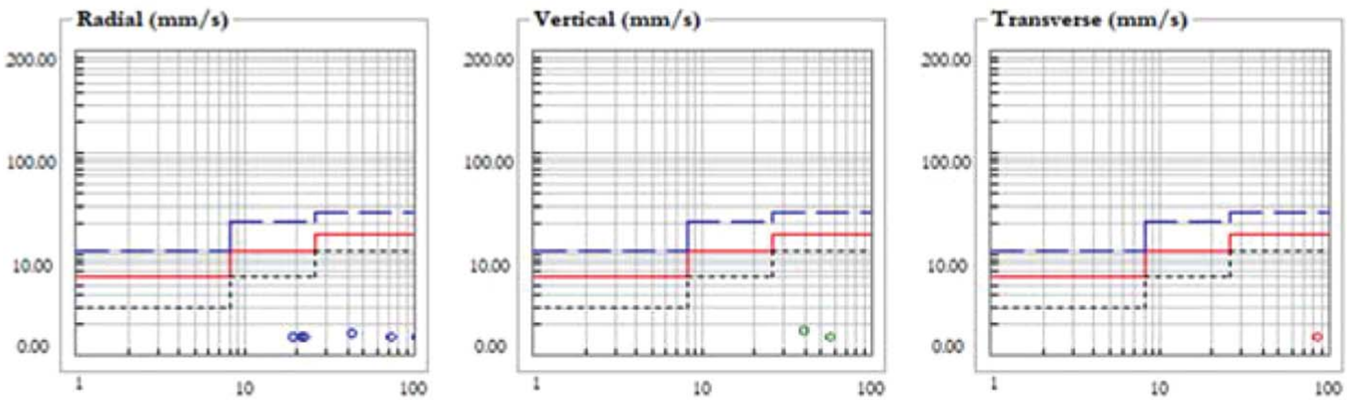

Fig.21: Frequency vs. amplitude plot at distance 900m

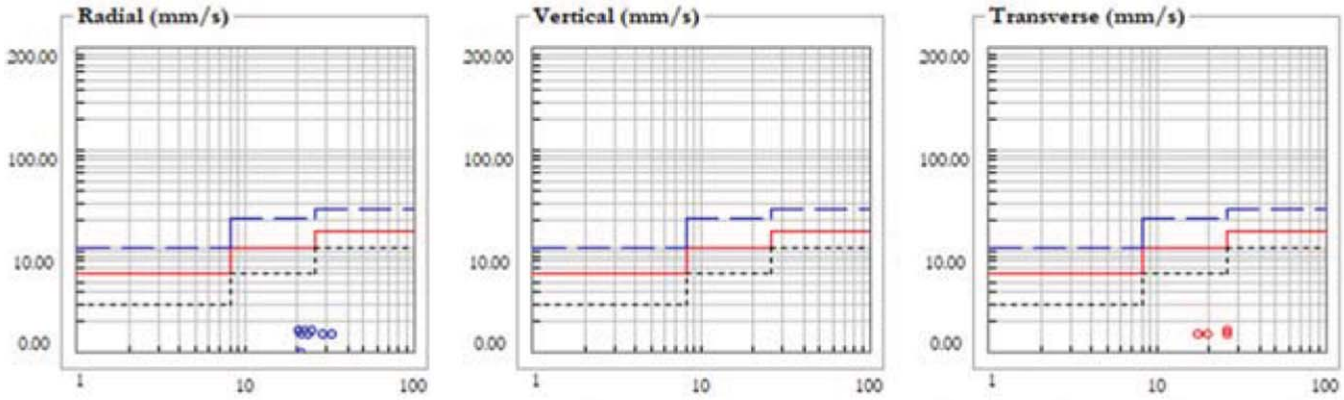

Fig.22: Frequency vs. amplitude plot at distance 1350m **Frequency (Hz)**

frequencies 3.90Hz and 20.4Hz at 900m and 1350m distance, respectively. In all cases, resultant velocity (<1 mm/s) is too low it means the effect is negligible on any types of structures.

6.0 Conclusion

It has been predicted that the MVRA values are in close proximity with measured peak particle velocity as compared to the other two predictor model. Conventional method depends on only two parameters and are not influenced by the above mentioned other parameters. Besides, the conventional plot provides reliable relationship between component velocity and frequency for better understanding of damage criteria and blast-induced ground vibration level. The MVRA gives better correlation than the USBM and IS (DGMS). But, all models are more helpful to optimization of blast design parameter of particular site. The derived site characteristics constant cannot be applied for different location because the physical properties of rockmass change from one place to another place.

7. Acknoledgement

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