CHAPTER 5

RESULTS AND DISCUSSION FOR PEAK PARTICLE VELOCITY (PPV)

5.1 Results obtained for all the quarries

The PCA and SSE followed by Multi-variate linear regression and ANN techniques have been employed to determine the blasting design and explosive parameters affecting ground vibrations. The equations developed by PCA and SSE have been used for validation (within the statistical domain) and the multi-layer perceptron (MLP) ANN technique has been used for verification outside the statistical domain. Further, the predicted values of PPV by PCA and SSE have been compared with the PPV values predicted by standard USBM square root equation. The results followed by discussion is presented in this chapter for all the three quarries.

In this research work, 19 blasting design parameters has been used. Some parameters are dependent on the other parameters like S/B, T/B, H/B depends on Burden (B). The PCA and SSE techniques has been carried out on these 19 parameters to select those, which are independent and not correlated among each other. For this, the term called variance inflation factor (VIF), which indicates the multi collinearity among parameters has been used to select the independent parameters. The VIF< 10, shows there is no any multicollinearity and VIF>10 shows the multicollinearity. So, the parameters which have VIF value less than 10 has been selected to develop the equation for the prediction of PPV and PF and other parameters has been rejected. By this way only independent parameters has selected at the final stage.

During the field studies, it was observed that the engineered Burden, Spacing and other blast geometry dimensions could not be implemented in real time (field blasting) because of:

i. Site constraints such as undulated free face geometry, blast hole deviation etc.

ii. Operations problem such as explosive variation, fixed diameter drilling, seasonal variations etc.

iii. Poor supervision such as lack of correct measurement in CCL, S, B, T lengths etc.

Various researchers have used S, B, and various blasting ratios together in analysing the blasting results in terms of fly rock, air overpressure, peak particle velocity etc. (Adhiakri, 1999, Segarra et. al; 2010, Hudaverdi, 2012, Hudaverdi and Akyilidiz, 2021, Jiang et, al; 2021)

To further substantiate the inclusion of S, B and other blasting ratios in the study, it may be consequential to mention the point of dependencies of blasting ratios of Burden was duly considered and the S and B values were not included for a trial statistical run in the PCA and SSE techniques, despite their VIF values being less than 10. The R^2 value by the given exclusion was found to be much lower (0.42 for PCA and 0.39 for SSE). Therefore, all the input variables which have VIF<10, have been considered in the present study as input parameters. Range of reduction in the input parameters is from 50 to 60% by PCA and from 45 to 55 by SSE techniques with 19 blasting design parameters. Table 5.1 represents the primary descriptive statistics of the input blasting design parameters and the output parameter (PPV and PF).

Table 5.1: Principal descriptive statistics of the blasting data set for prediction of PPV and PF (Quarry A, B and C)

				Symbols	Quarry A			Quarry B			Quarry C		
		S.No.			Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean
Input	Blast design parameters	1	Burden (m)	B	3.00	4.00	3.34	3.00	4.50	3.59	3.00	3.50	3.34
		2	Blast hole diameter (mm)	D	115.0	150.0	118.27	110.0	150.0	124.89	110.0	115.0	114.08
		3	Spacing (m)	S	4.0	5.0	4.40	3.90	6.00	4.82	4.00	5.50	4.97
		4	Bench height (m)	H	10.0	11.0	10.38	10.0	11.0	10.04	9.0	10.5	9.68
		5	Stemming (m)	T	3.70	4.60	4.22	3.20	4.90	3.88	2.83	4.73	3.80
		6	S/B ratio	S/ B	1.20	1.40	1.31	1.20	1.50	1.33	1.20	1.60	1.49
		7	T/B ratio	T/ B	0.78	1.29	1.02	0.80	1.31	1.03	0.84	1.29	1.08
		8	H/B ratio	H/ B	2.50	3.70	3.12	2.20	3.70	2.84	2.50	3.50	2.91
		9	T/CCL ratio	T/CCL	0.53	0.81	0.68	0.47	0.81	0.63	0.45	0.85	0.65
		10	No. of Rows	Nr	2.0	5.0	2.85	2.0	4.0	2.24	2.0	4.0	2.46
		11	No. of Holes	Nh	15.0	45.0	24.61	12.0	35.0	19.10	15.0	36.0	20.43
		12	Distance (m)	Di	150.0	500.0	352.65	200.0	400.0	299.52	140.0	350.0	218.92
		13	Inter Hole delay (ms)	HD	17.0	25.0	17.64	17.0	42.0	36.68	17.0	25.0	17.12
		14	Inter Row delay (ms)	RD	25.0	42.0	32.93	25.0	65.0	62.97	25.0	42.0	28.92
		15	Scaled distance (m/Kg$^{1/2}$)	SD	19.20	67.30	45.73	25.20	56.20	38.86	19.80	48.60	38.28
	Explosive parameters	16	Column charge length (m)	CCL	5.50	6.90	6.15	5.50	6.80	5.15	4.30	6.80	5.83
		17	Total amount of explosive(Kg)	Qe	727.80	3328.50	1334.20	530.40	1955.00	1008.12	536.10	1305.00	746.91
		18	Charge per delay (Kg)	CPD	49.0	92.84	59.79	45.20	96.70	63.04	40.30	56.70	49.06
Output		1.	Peak Particlevelocity (mm/s)	PPV	0.60	4.20	1.96	0.70	4.80	2.51	0.74	4.50	2.18
		2.	Powder factor (Kg/t)	PF	0.15	0.31	0.22	0.12	0.28	0.18	0.11	0.21	0.14

5.2 Results from PCA technique

5.2.1 Results obtained for quarry A using PCA

PCA led to the generation of 7 principal component (PC) groups with eigen values of greater than 1.0, which is illustrated by scree plot in Figure 5.1. These 7 PC groups accounted for 93.333% cumulative variance in blasting design parameters. Table 5.2 illustrates the data matrix explaining the variance and the number of PC groups.

Table 5.2: Data matrix explaining variance for the study quarry A (for PPV prediction)

PC Group	Initial Eigenvalues and Variance		
	Total	% of Variance	Cumulative %
1	**5.536**	29.136	29.136
2	**3.821**	20.110	49.246
3	**2.689**	14.153	63.399
4	**1.833**	9.649	73.048
5	**1.478**	7.780	80.828
6	**1.336**	7.031	87.859
7	**1.040**	5.474	**93.333**
8	.638	3.355	96.688
9	.488	2.567	99.255
10	.079	.415	99.670
11	.029	.155	99.825
12	.019	.099	99.924
13	.008	.041	99.964
14	.003	.016	99.980
15	.002	.011	99.992
16	.001	.005	99.997
17	.001	.003	100.000
18	6.339E-005	.000	100.000
19	-9.246E-016	-4.866E-015	100.000

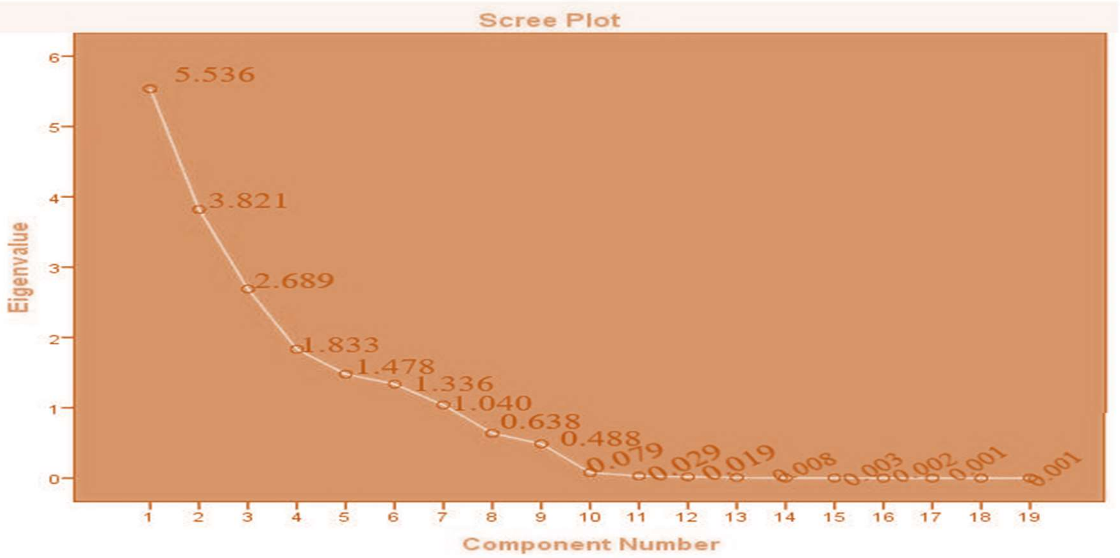

Figure 5.1: Scree plot indicating PC groups for PPV in quarry A

Table 5.3 illustrates the 7 PC groups with the coefficient of determination (R^2) values for all the blasting design parameters. As such, the PCs were identified from each component group based on the value of R^2.

Table 5.3: Identification of PCs in the study quarry A (for PPV prediction)

Blasting design parameters	PC groups with regression coefficients						
	1	2	3	4	5	6	7
B	0.955	-.174	.064	.122	.054	-.159	.082
D	0.745	.057	-.067	.249	.308	.437	-.161
S	0.908	-.092	.076	.118	-.080	-.222	.035
H	-0.203	-.072	.816	.206	.457	-.137	-.090
T	-0.354	-.314	-.202	.530	.598	-.290	-.022
CCL	-0.020	.096	.975	-.074	.154	.014	-.083
S/B	-.597	.295	-.026	-.065	-.310	-.023	-.172
T/B	-.931	.017	-.157	.157	.261	.048	-.093
H/B	-.920	.142	.255	-.013	.161	.146	-.130
T/CCL	-.195	-.251	-.924	.357	.225	-.186	.057
Nr	.060	.910	-.025	.275	-.011	-.172	.138
Nh	.027	.921	-.005	.255	-.047	-.152	.168
Qe	.297	.982	.025	.329	.013	.037	.089
Di	.351	.477	-.238	-.657	.392	-.207	-.283
CPD	.771	.037	.006	.193	.264	.548	-.191
HD	-.101	.139	.178	-.265	.310	-.045	.771
RD	-.037	-.161	-.254	-.444	.334	.593	.319
PF	-.350	.723	-.190	.096	.007	.500	-.061
SD	.161	.493	-.242	-.620	.330	-.340	-.247

A total number of 16 PCs were identified and extracted from the Table 5.4, namely B, S, T/B, H/B, Nr, Nh, Qe, CCL, T/CCL, SD, Di, T, PF, RD, CPD and HD. These 16 PCs have been grouped into 7 PC groups based on the R^2 values. The results of 7 PC groups is tabulated in Table 5.5.

Table 5.4: The 7 identified PC groups by PCA for PPV (quarry A)

Principal Component Group-1	B, S, T/B, H/B
Principal Component Group -2	Nr, Nh, Qe
Principal Component Group -3	CCL, T/CCL
Principal Component Group -4	SD, Di
Principal Component Group -5	T
Principal Component Group -6	PF, RD, CPD
Principal Component Group -7	HD

The MLR analysis for PPV prediction carried out for all the identified 16 PCs [B, S, T/B, H/B, Nr, Nh, Qe, CCL, T/CCL, SD, Di, T, PF, RD, CPD and HD], revealed multi-collinearity. Therefore, after eliminating multi-collinearity, MLR analysis for PPV prediction has been carried out for the retained 7 PCs [S, T/B, Qe, CPD, B, CCL and Di].

Table 5.5 summarizes the MLR analysis results for all the identified 16 PCs. It is revealed that an acute multi-collinearity was associated with some of these PCs.

Table 5.5: MLR results for all the identified 16 PCs

Model	R	R Square	Adjusted R Square	Significance	Std. Error of the Estimate
1	0.879	0.773	0.710	0.00	0.57169

From the analysis, it has been found that 9 out of 16 PCs were having multi-collinearity (VIF>10). Therefore, 9 PCs were rejected because they contained multi-collinearity among them (Table 5.6).

Table 5.6: Blast design parameters with multi-collinearity (VIF>10) for PPV (quarry A)

S.No.	Blasting design parameters	VIF values
1	H/B	13.62
2	Nr	12.15
3	Nh	14.36
4	T/CCL	10.25
5	SD	11.23
6	T	16.13
7	PF	22.39
8	HD	15.62
9	RD	14.96

Accordingly, the new prediction equation has been developed after removing the 9 PCs, which contained multi-collinearity. As such, 7 PCs [S, T/B, Qe, CPD, B, CCL and Di] have been identified, which were free from multi-collinearity (Table 5.7).

Table 5.7: Blast design parameters without multi-collinearity (VIF<10) for PPV (quarry A)

S.No.	Blasting design parameters	VIF values
1	S	1.066
2	T/B	3.673
3	Qe	1.279
4	CPD	3.121
5	B	4.130
6	CCL	6.357
7	Di	1.195

The MLR technique has thus been applied on the 7 identified parameters to develop the equation, subsequently the unstandardized coefficients of the selected blasting design parameters together with their significance value and standard error have been derived. Table 5.8 presents the results in terms of the unstandardized coefficients with the significance, standard error and collinearity statistics of the identified blasting design parameters.

Table 5.8: Descriptive statistics of 7 parameters for developing predictor Eq. for PPV

Blasting design parameters	Unstandardized Coefficients		Significance level	Collinearity Statistics	
	B	Std. Error		Tolerance	VIF
(Constant)	0.645	3.636	.860		
S	-1.022	.650	.120	.899	1.066
T/B	1.016	5.487	.000	.218	3.673
Qe	0.001	.000	.000	.782	1.279
CPD	0.012	.012	.314	.320	3.121
B	0.591	2.215	.004	.310	4.130
CCL	0.133	1.182	.001	.315	6.357
Di	-0.008	.001	.000	.837	1.195

The developed equation in the form of equation using unstandardized regression coefficient (β-value) associated with 7 retained PCs (as illustrated in Table 5.8) is presented in Eq.5.1:

$$PPV = 0.645 - S \times (1.022) + \frac{T}{B} \times (1.016) + Qe \times (0.001) + CPD \times (0.012) + B \times (0.591) + CCL \times (0.133) - Di \times (0.008) \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (\mathbf{5.1})$$

The MLR analysis results for the developed equation has been presented in Table 5.9.

Table 5.9: MLR based descriptive statistics for the parameters used in Eq. 5.1

Model	R	R Square	Adjusted R Square	Significance	Std. Error of the Estimate	F
1	0.859	0.738	0.706	0.00	0.57554	22.976

It is noteworthy that the value of (R^2) is 0.738 and adjusted (R^2) is 0.706 for the developed equation. The significance level is 0.00 and the F-value has been observed as 22.976, which strengthens the obtained results.

5.2.2 Results obtained for quarry B using PCA

PCA led to the generation of 6 PC groups with eigen value greater than 1.0, which is illustrated by scree plot in Figure 5.2. The 6 PC groups accounted for 86.527 % cumulative variance in blasting design parameters. Table 5.10 illustrates the data matrix explaining the total variance and the number of PC groups.

Table 5.10: Data matrix explaining variance for the study quarry B (for PPV prediction)

Principal Component Group	Initial Eigenvalues and variance		
	Total	% of Variance	Cumulative %
1	**6.709**	35.313	35.313
2	**3.457**	18.193	53.505
3	**2.372**	12.486	65.991
4	**1.522**	8.009	74.000
5	**1.322**	6.956	80.956
6	**1.058**	5.571	**86.527**
7	.996	5.241	91.768
8	.535	2.814	94.582
9	.453	2.385	96.967
10	.314	1.653	98.620
11	.116	.609	99.229
12	.105	.555	99.784
13	.019	.098	99.883
14	.009	.048	99.931
15	.006	.030	99.961
16	.004	.020	99.981
17	.002	.009	99.990
18	.001	.006	99.996
19	.001	.004	100.000

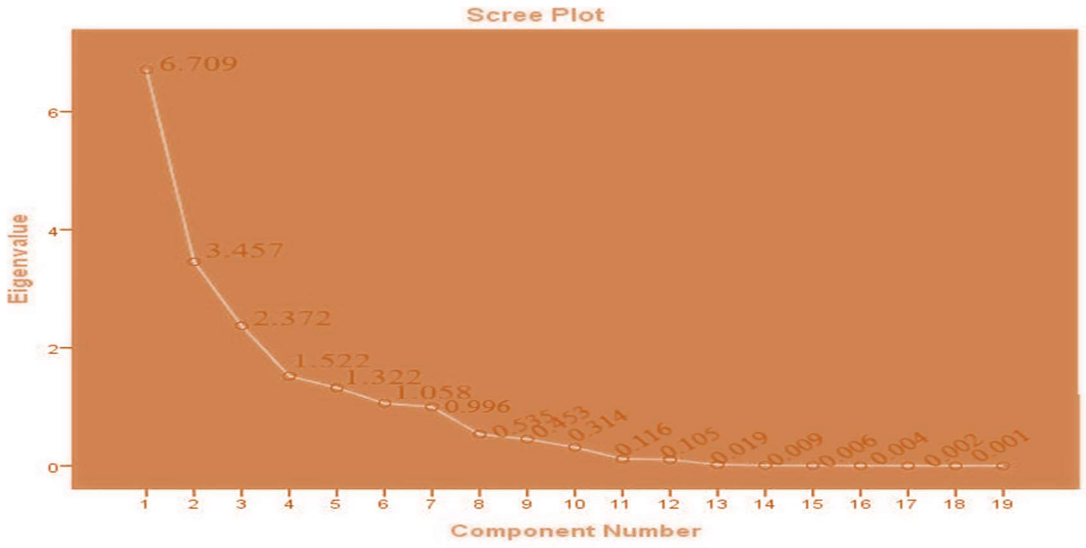

Figure 5.2: Scree plot indicating principal component groups for PPV in quarry B

Table 5.11 illustrates the 6 PC groups with the coefficient of determination (R^2) values for all the blasting design parameters. As such, the PCs were identified from each component group based on the value of R^2.

Table 5.11: Identification of PCs in the study quarry B (for PPV prediction)

Blasting design parameters	PC groups with regression Coefficient					
	1	2	3	4	5	6
B	-.976	.045	.154	-.064	-.043	.034
D	-.941	.135	.150	-.017	.010	-.124
S	-.938	-.054	.154	.000	-.041	.270
H	-.074	.238	.322	.723	.003	.009
T	-.266	.864	-.242	.314	-.123	.044
CCL	.229	-.879	.456	.055	.128	-.041
S/B	.282	-.340	-.098	.224	.014	.782
T/B	.797	.444	-.288	.216	-.002	-.045
H/B	.968	-.014	-.105	.147	.050	-.034
T/CCL	-.264	.863	-.350	.184	-.128	.053
NR	.372	.273	.791	.128	-.168	.174

NH	.441	.266	.797	-.023	-.139	.170
Q	.012	.388	.786	.069	-.109	-.073
Di	-.008	.516	.143	-.722	.032	.121
CPD	-.930	.042	.220	-.016	.036	-.137
HD	-.002	.434	.242	-.057	.684	.161
RD	-.016	.159	.019	.153	.857	-.082
PF	.728	.114	.293	.009	-.063	-.436
SD	.643	.419	-.035	-.552	.004	.764
DF	-.604	.614	.022	.207	.275	-.051
SD	-.707	.603	-.061	.030	-.168	-.132

A total number of 16 PCs were identified and extracted from the Table 5.11, namely B, D, S, H/B, CPD, T, T/CCL,CCL, Qe, Nr, Nh, Di, H, RD, S/B and SD. These 16 PCs have been grouped into 6 PC groups based on the R^2 values. The results of 6 PC groups is tabulated in Table 5.12.

Table 5.12: The 6 identified PC groups by PCA for PPV (quarry B)

Principal Component Group -1	B, D, S, H/B, CPD
Principal Component Group -2	T, T/CCL, CCL
Principal Component Group -3	Qe, Nr, Nh
Principal Component Group -4	Di, H
Principal Component Group -5	RD
Principal Component Group -6	S/B, SD

The MLR analysis for PPV prediction carried out for all the identified 16 PCs [B, D, S, H/B, CPD, T, T/CCL, CCL, Qe, Nr,Nh, Di, H, RD, S/B and SD], revealed multi-collinearity. Therefore, after eliminating the multi-collinearity, MLR analysis for PPV prediction has been carried out for the retained 9 PCs [Nh, RD, T/CCL, B, SD, CPD, QE and S]

Table 5.13 summarizes the MLR analysis results for all the identified 16 PCs. It is revealed that an acute multi-collinearity was associated with some of these PCs.

Table 5.13: MLR results for all the identified 16 PCs

Model	R	R Square	Adjusted R Square	Significance	Std. Error of the Estimate
1	0.909	0.826	0.781	0.00	0.49431

From the analysis, it has been found that 7 out of 16 PCs were having multi-collinearity (VIF >10). Therefore, 7 PCs were rejected because they contained multi-collinearity among input variables (Table 5.14).

Table 5.14: Blast design parameters with multi-collinearity (VIF >10) for PPV (quarry B)

S.No.	Blasting design parameters	VIF values
1	D	14.62
2	H/B	19.15
3	T	18.36
4	CCL	11.25
5	Di	13.23
6	H	10.13
7	S/B	20.39

Accordingly, the new prediction equation was developed after removing the 7 PCs, which contained multi-collinearity. As such, 9 PCs [Nh, RD, T/CCL, B, SD, CPD, QE and S] have been selected, which were free from multi-collinearity (Table 5.15).

Table 5.15: Blast design parameters without multi-collinearity (VIF <10) for PPV (quarry B)

S.No.	Blasting design parameters	VIF values
1	Nh	1.790
2	RD	1.041
3	T/CCL	1.288
4	Di	5.587
5	B	9.724
6	SD	8.232
7	CPD	4.407
8	Qe	1.734
9	S	1.549

The MLR technique thus has been applied on the 9 identified parameters to develop the equation, subsequently the unstandardized coefficients of the selected blasting design parameters together with their significance value and standard error have been derived. Table 5.16 presents the results in terms of the unstandardized coefficients with the significance, standard error and collinearity statistics of the selected blasting design parameters.

Table 5.16: Descriptive statistics of 9 parameters for developing predictor Eq. for PPV

Blasting design parameters	Unstandardized Coefficients		Significance	Collinearity Statistics	
	B	Std. Error		Tolerance	VIF
(Constant)	5.379	3.763	.157		
Nh	.002	.016	.201	.559	1.790
RD	-.013	.007	.069	.961	1.041
T/CCL	.951	.823	.252	.777	1.288
Di	-.014	.009	.120	.520	5.587
B	1.799	1.078	.100	.311	9.724
SD	-.231	.069	.001	.612	8.232
CPD	.068	.021	.023	.422	4.407
Qe	.002	.000	.000	.577	1.734
S	-1.489	.772	.058	.112	1.549

The developed equation in the form of equation using unstandardized regression coefficient (β-value) associated with 9 retained PCs (as illustrated in Table 5.16), is presented in Eq.5.2:

$$PPV = 5.379 + Nh \times (0.002) - RD \times (0.013) + \frac{T}{CCL} \times (0.951) - Di \times (0.014) + B \times (1.799) - SD \times (0.231) + CPD \times (0.068) + Qe \times (0.002) - S \times (1.489) \qquad (\mathbf{5.2})$$

The MLR analysis results for the developed equation have been presented in Table 5.17.

Table 5.17: MLR based descriptive statistics for the parameters used in Eq.5.2

Model	R	R Square	Adjusted R Square	Significance	Std. Error of the Estimate	F
1	0.901	0.811	0.766	0.00	0.51185	23.964

It is noteworthy that the value of R^2 is 0.811 and adjusted R^2 is 0.766 for the developed equation. The significance level was 0.00 and the F-value has been observed as 23.964, which strengthen the obtained results.

5.2.3 Results obtained for quarry C using PCA

PCA led to the generation of 7 PC groups with eigen value greater than 1.0, which is illustrated by scree plot in Figure 5.3. These 7 PC groups accounted for 89.690 % cumulative variance in blasting design parameters. Table 5.18 illustrates the data matrix explaining the variance and the number of PC groups.

Table 5.18: Data matrix explaining variance for the study quarry C (for PPV prediction)

Principal component groups	Initial Eigenvalues and variance		
	Total	% of Variance	Cumulative %
1	**4.751**	25.005	25.005
2	**3.190**	16.790	41.795
3	**2.675**	14.080	55.875
4	**2.059**	10.836	66.712
5	**1.770**	9.318	76.030
6	**1.540**	8.107	84.136
7	**1.055**	5.554	**89.690**
8	.866	4.557	94.247
9	.691	3.639	97.885
10	.240	1.263	99.148
11	.078	.413	99.561
12	.037	.197	99.757
13	.031	.161	99.919
14	.008	.044	99.963
15	.004	.021	99.984
16	.002	.009	99.993
17	.001	.004	99.997
18	.000	.002	99.999
19	.000	.001	100.000

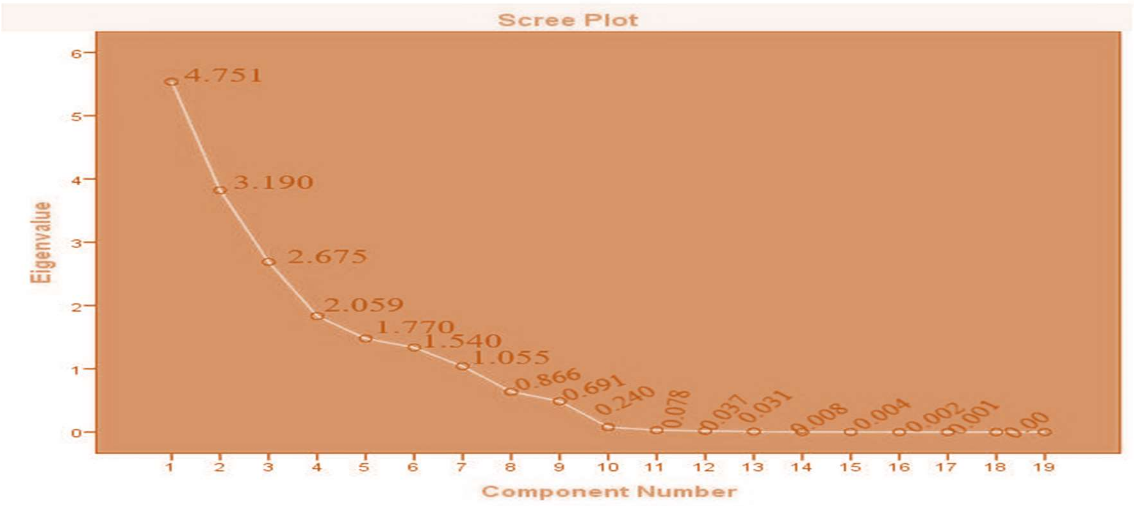

Figure 5.3: Scree plot indicating principal component groups for PPV in quarry C

Table 5.19 illustrates the PC groups with the coefficient of determination (R^2) values for all the blasting design parameters. As such, the PCs were identified from each component group based on the value of R^2.

Table 5.19: Identification of PCs in the study quarry C (for PPV prediction)

Blasting design parameter	PC groups with regression coefficient						
	1	2	3	4	5	6	7
B	-.713	.169	-.161	.691	.190	-.062	-.059
D	-.053	.020	.152	-.020	-.649	.110	.337
S	-.402	.215	-.278	.359	-.267	.782	-.052
H	.547	.148	.528	.624	-.068	-.059	-.248
T	.977	-.253	-.039	.531	.003	-.015	-.093
CCL	-.209	.473	.796	.082	-.061	-.082	-.190
S/B	.316	.040	-.123	-.245	-.459	.735	.004
T/B	.937	-.280	.051	.122	-.093	.018	-.047
H/B	.949	-.056	.407	-.185	-.183	.014	-.089
T/CCL	.701	-.406	-.416	.360	.026	.034	.016
Nr	.405	.799	-.164	-.029	.321	.138	-.026
Nh	.411	.811	-.174	-.006	.284	.172	.021
Qe	.419	.828	-.168	-.057	.233	.078	.044
CPD	-.228	.427	.768	.035	-.347	-.025	.025
Di	-.042	-.380	.595	-.074	.521	.422	.156
HD	.040	.188	.026	.280	.018	-.120	.789
RD	.321	.068	.167	.449	-.041	-.108	.347
PF	.524	.094	-.032	-.694	.000	-.240	.161
SD	-.008	-.448	.470	-.080	.690	.434	.149

A total number of 15 PCs were identified and extracted from the Table 5.19, namely 15 PCs namely T/B, H/B, T, Nh, Qe, CCL, CPD, B, H, PF, D, SD, S, S/B and HD. These 15 PCs have been grouped into 7 PC groups based on the R^2 values. The result of 7 PC groups is tabulated in Table 5.20.

Table 5.20: The 7 identified PC groups by PCA for PPV (quarry C)

Principal Component Group-1	T/B, H/B, T
Principal Component Group -2	Nh, Qe
Principal Component Group -3	CCL, CPD
Principal Component Group -4	B, H, PF
Principal Component Group -5	D, SD
Principal Component Group -6	S, S/B
Principal Component Group – 7	HD

The MLR analysis for PPV prediction carried out for all the identified 15 PCs [T/B, H/B, T, Nh, Qe, CCL, CPD, B, H, PF, D, SD, S, S/B and HD], revealed multi-collinearity. Therefore, after eliminating the multi-collinearity, MLR analysis for PPV prediction has been carried out for the retained 9 PCs [Nh, Qe, CCL, CPD, H, D, SD, H/B and HD].

Table 5.21 summarizes the MLR analysis results for all the identified 15 PCs. It is revealed that an acute multi-collinearity was associated with some of these PCs.

Table 5.21: MLR results for all the identified 15 PCs

Model	R	R Square	Adjusted R Square	Significance level	Std. Error of the Estimate
1	0.926	0.857	0.785	0.00	0.550843

From the analysis, it has been found that 6 out of 15 PCs were having multi-collinearity (VIF>10). Therefore, 6 PCs were rejected because they contained multi-collinearity among input variables (Table 5.22).

Table 5.22: Blast design parameters with muti-collinearity (VIF >10) for PPV (quarry C)

S.No.	Blasting design parameters	VIF values
1	T/B	11.85
2	T	13.25
3	B	10.96
4	PF	22.15
5	S	17.25
6	S/B	11.49

Accordingly, the new prediction equation has been developed after removing the 6 PCs, which contained multi-collinearity. As such, 9 PCs [H, Di, RD, S, Nr, T/CCL, Qe, D and Vr] have been identified, which were free from multi-collinearity (Table 5.23).

Table 5.23: Blast design parameters without multi-collinearity (VIF <10) for PPV (quarry C)

S.No.	Blasting design parameters	VIF values
1	Nh	1.412
2	Qe	1.756
3	CCL	1.444
4	CPD	1.152
5	H	1.440
6	D	3.687
7	SD	1.183
8	S/B	1.496
9	HD	1.043

The MLR technique thus has been applied on the 9 identified parameters to develop the equation, subsequently the unstandardized coefficients of the selected blasting design parameters together with their significance value and standard error have been derived. Table 5.24 presents the results in terms of the unstandardized coefficients with the significance, standard error and collinearity statistics of the selected blasting design parameters.

Table 5.24: Descriptive statistics of 9 parameters for developing predictor Eq. for PPV

Blasting design parameters	Unstandardized Coefficients		Significance level	Collinearity Statistics	
	B	Std. Error		Tolerance	VIF
(Constant)	-.391	8.726	.964		
Nh	.136	.051	.011	.275	1.412
Qe	.003	.002	.100	.173	1.756
CCL	.111	.632	.862	.587	1.444
CPD	.062	.079	.511	.476	1.152
H	.381	.194	.055	.694	1.440
D	-.032	.077	.683	.271	3.687
SD	-.051	.012	.000	.846	1.183
S/B	2.281	.906	.015	.668	1.496
HD	-.105	.081	.202	.959	1.043

The equation developed in the form of equation using unstandardized regression coefficient (β-value) associated with 9 retained PCs (as illustrated in Table 5.24), is presented in Eq.5.3:

$$PPV = -0.391 + Nh \times (0.136) + Qe \times (0.003) + CCL \times (0.111) + CPD \times (0.062) + H \times (0.381) - D \times (0.032) - SD \times (0.051) + \frac{S}{B} \times (2.281) - HD \times (0.105) \qquad \mathbf{(5.3)}$$

The MLR analysis results for the developed equation has been presented in Table 5.25.

Table 5.25: MLR based descriptive statistics for the parameters used in Eq. 5.3

Model	R	R Square	Adjusted R Square	Significance level	Std. Error of the Estimate	F
1	0.911	0.829	0.757	0.00	0.44124	22.759

It is noteworthy that the value of R^2 has been found to be 0.829 and adjusted R^2 has been found as 0.757 for the developed equation. The significance level has been found to be 0.00 and F- value has been found as 22.759, which improves the authenticity of the predictor equation.

5.3 Results from SSE technique

5.3.1 Results obtained for quarry A using SSE

In order to determine the significantly correlating blasting design parameters that showed significance [(2-tailed) ≤ 0.05], the bivariate correlation technique using Pearson's correlation has been applied. The correlation matrix in Table 5.26 presents the results of significance values of all the blasting design parameters with respect to PPV, sig. (2-tailed).

Table 5.26: Correlation matrix with significance values with respect to PPV (quarry A)

Blasting design Parameters	PPV	Significance
	Pearson's correlation	(2-tailed)
B	-0.208	0.004
D	0.034	0.770
S	0.163	0.001
H	0.125	0.284
T	0.217	0.000
CCL	0.013	0.909
S/ B	0.208	0.001
T/ B	0.286	0.003
H/ B	0.253	0.028
T/CCL	0.105	0.372
Nr	0.203	0.002
Nh	0.219	0.059
Qe	0.211	0.000
Di	-0.667	0.000
CPD	0.081	0.492
HD	-0.094	0.520
RD	-0.049	0.678
PF	0.258	0.026
SD	-0.658	0.000

Nine parameters [B, S, T, S/B, T/B, Nr, Qe, Di and SD] have been identified having sig. ≤ 0.05, as revealed from Table 5.26. The results of the MLR for PPV prediction performed on the 9 identified parameters have been summarized in Table 5.27.

Table 5.27: MLR results for predicting PPV using the identified 9 parameters

Model	R	R Square	Adjusted R Square	Significance	Std. Error of the Estimate
1	0.854	0.729	0.691	0.00	0.58990

MLR analysis reveals multi-collinearity in 3 out of 9 parameters. The values of VIF for the 3 parameters, which revealed multi-collinearity, are tabulated in Table 5.28.

Table 5.28: Blast design parameters with multi-collinearity (VIF>10) for PPV (quarry A)

S.No.	Blasting design parameters	VIF values
1	B	13.62
2	S	12.15
3	T/B	14.36

Consequently, after removal of the 3 parameters exhibiting multi-collinearity, only the 6 parameters [SD, S/B, T, Qe, Nr and Di] identified having no multi-collinearity are summarized in Table 5.29.

Table 5.29: Blast design parameters free from multi-collinearity VIF<10 for PPV (quarry A)

S.No.	Blasting design parameters	VIF values
1	T	2.178
2	S/B	1.816
3	Nr	6.996
4	Qe	8.048
5	Di	4.349
6	SD	6.654

As such, the unstandardized coefficients of the identified blasting design parameters together with their significance value and standard error are presented in Table 5.30.

Table 5.30: Descriptive statistics of 6 parameters for developing predictor Eq. for PPV (quarry A)

Blasting design parameters	Unstandardized Coefficients		Significance	Collinearity Statistics	
	B	Std. Error		Tolerance	VIF
(Constant)	-2.431	3.652	.508		
T	.358	.510	.485	.459	2.178
S/B	2.105	2.311	.366	.551	1.816
Nr	.074	.332	.824	.159	6.996
Qe	.001	.001	.074	.155	8.048
Di	-.005	.005	.284	.222	4.349
SD	-.020	.037	.599	.121	6.654

The developed model in the form of equation using unstandardized regression coefficient (β-value) associated with 6 retained PCs (as illustrated in Table 5.30), is presented in Eq.5.4:

$$PPV = -2.431 + (0.358) \times T + (2.105) \times \frac{S}{B} + (0.074) \times Nr + (0.001) \times Qe - (0.005) \times Di - (0.020) \times SD \quad \mathbf{(5.4)}$$

The MLR analysis results for the developed equation is presented in Table 5.31.

Table 5.31: MLR based descriptive statistics the parameters used in equation for Eq. 5.4

Model	R	R Square	Adjusted R Square	Significance	Std. Error of the Estimate	F
1	0.825	0.681	0.648	0.00	0.63007	20.427

A close perusal of the value of R^2 has been found to be 0.681 and adjusted R^2 has been found as 0.648. Furthermore, the F-ratio has been found as 20.427 which is much greater than 4 and the significance level was 0.00, which improves the authenticity of the predictor equation.

Since, these 6 parameters were introduced sequentially, therefore it may be consequential to state that with the addition of each parameter, the value of R^2 increased from 0.207 to 0.681, as clearly revealed in Table 5.32.

Table 5.32: Summary of models prepared by MLR using SSE for PPV (quarry A)

Model	R value	R Square Value	Adjusted R Square value	Significance level	F value	Predictor constants
1	0.456	0.207	0.166	0.004	11.714	T
2	0.498	0.248	0.213	0.002	13.651	T+S/B
3	0.588	0.345	0.310	0.006	14.654	T+S/B +Nr
4	0.646	0.417	0.374	0.005	15.562	T+S/B +Nr+Qe
5	0.712	0.506	0.459	0.000	17.452	T+S/B +Nr+Qe+Di
6	**0.825**	**0.681**	**0.648**	**0.000**	**20.427**	T+S/B +Nr+Qe+Di+SD

5.3.2 Results obtained for quarry B using SSE

The correlation matrix in Table 5.33 presents the significance values [(sig. (2-tailed)] of all the blasting design parameters with respect to PPV.

Table 5.33: Correlation matrix with significance values with respect to PPV (quarry B)

Blasting design Parameters	PPV	Significance
	Pearson's correlation	(2-tailed)
B	0.210	0.006
D	0.232	0.010
S	0.721	0.100
H	0.242	0.011
T	0.427	0.746
CCL	0.120	0.000
S/ B	0.089	0.004
T/ B	-0.176	0.011
H/ B	-0.235	0.060
T/CCL	0.033	0.006

Nr	0.381	0.002
Nh	0.186	0.001
Qe	0.483	0.000
Di	-0.513	0.000
CPD	0.255	0.001
HD	0.073	0.520
RD	-0.067	0.969
PF	0.094	0.412
SD	-0.586	0.003

Thirteen parameters [B, D, H, CCL, S/B, T/B, T/CCL, Nr, Nh, Qe, Di, CPD and SD] have been identified having sig. ≤ 0.05, as revealed from Table 5.33. The results of the MLR for PPV prediction has been performed on the 13 identified have been summarized in Table 5.34

Table 5.34: MLR results for predicting PPV using the identified 13 parameters

Model	R	R Square	Adjusted R Square	Significance	Std. Error of the Estimate
1	0.883	0.779	0.735	0.00	0.543840

MLR analysis reveals multi-collinearity in 7 out of 13 parameters. The values of VIF for the 7 parameters, which revealed multi-collinearity, are tabulated in Table 5.35.

Table 5.35: Blast design parameters with multi-collinearity (VIF >10) for PPV (quarry B)

S.No.	Blasting design parameters	VIF values
1	B	15.36
2	D	12.25
3	H	19.36
4	T/B	10.98
5	Nr	18.15
6	CCL	12.65
7	Di	10.65

Consequently, after removal of the 7 parameters exhibiting multi-collinearity, only the 6 parameters [S/B, T/CCL, Nh, CPD, SD and Qe] identified having no multi-collinearity are summarized in Table 5.36.

Table 5.36: Blast design parameters without multi-collinearity (VIF <10) for PPV (quarry B)

S.No.	Blasting design parameters	VIF values
1	S/B	1.262
2	T/CCL	1.940
3	Nh	1.795
4	CPD	6.081
5	SD	1.950
6	Qe	1.842

As such, the unstandardized coefficients of the selected blasting design parameters together with their significance value and standard error are presented in Table 5.37. This table presents the unstandardized coefficients with the significance, standard error and collinearity statistics of the identified blasting design parameters.

Table 5.37: Descriptive statistics of 6 parameters for developing predictor Eq. for PPV

Blasting design parameters	Unstandardized Coefficients		Significance	Collinearity Statistics	
	β	Std. Error		Tolerance	VIF
(Constant)	11.480	5.145	.029		
S/B	-1.312	1.013	.199	.793	1.262
T/CCL	1.975	2.613	.452	.384	1.940
Nh	.019	.016	.236	.557	1.795
CPD	.017	.008	.036	.164	6.081
SD	-.127	.011	.000	.513	1.950
Qe	.002	.000	.000	.543	1.842

The developed model in the form of equation using unstandardized regression coefficient (β-value) associated with 6 retained PCs (as illustrated in Table 5.37), is presented in Eq.5.5:

$$PPV = 11.480 - \frac{S}{B} \times (1.312) + \frac{T}{CCL} \times (1.975) + Nh \times (0.019) + CPD \times (0.017) - SD \times (0.127) + Qe \times (0.002) \qquad \mathbf{(5.5)}$$

The MLR analysis for the developed equation is presented in Table 5.38.

Table 5.38: MLR based descriptive statistics for the parameters used in Eq. 5.5

Model	R	R Square	Adjusted R Square	Significance	Std. Error of the Estimate	F
1	0.868	0.753	0.725	0.00	0.554324	26.649

A close perusal of the valueof R^2 has been found to be 0.753 and adjusted R^2 has been found as 0.725. Furthermore, the F-ratio has been found to be 26.649 which is much greater than 4 and significance level was 0.00, which improves the authenticity of the predictor model.

Since these 6 parameters were introduced sequentially, therefore it may be consequential to state that with the addition of each parameter, the value of R^2 increased from 0.213 to 0.753, as clearly revealed in Table 5.39.

Table 5.39: Summary of models prepared by MLR using SSE for PPV (quarry B)

Model	R value	R Square value	Adjusted R Square value	Significance value	F value	Predictor constants
1	0.512	0.213	0.262	0.002	13.507	S/B
2	0.596	0.215	0.355	0.005	15.102	S/B+T/CCL
3	0.654	0.216	0.427	0.006	17.658	S/B+T/CCL+Nh
4	0.749	0.561	0.515	0.000	21.348	S/B+T/CCL+Nh+CPD
5	0.818	0.669	0.601	0.000	22.402	S/B+T/CCL+Nh+CPD+SD
6	**0.868**	**0.753**	**0.725**	**0.000**	**26.649**	S/B+T/CCL+Nh+CPD+SD+Qe

5.3.3 Results for quarry C using SSE

The correlation matrix in Table 5.40 presents the result of significance values [(sig. (2-tailed)] of all the blasting design parameters with respect to PPV.

Table 5.40: Correlation matrix with significance values with respect to PPV (quarry C)

Blasting design Parameters	PPV	Significance level
	Pearson correlation	(2-tailed)
B	-0.010	0.003
D	-0.048	0.706
S	0.230	0.000
H	0.158	0.209
T	0.266	0.001
CCL	0.120	0.673
S/ B	0.166	0.005
T/ B	0.085	0.501
H/ B	0.217	0.002
T/CCL	0.862	0.000
Nr	0.487	0.000
Nh	0.466	0.000
Qe	0.483	0.002
Di	0.157	0.001
CPD	-0.676	0.000
HD	0.112	0.374
RD	0.032	0.801
PF	-0.665	0.000
SD	0.586	0.112

Twelve parameters [B, S, T, S/B, H/B, T/CCL, Nr, Nh, Qe, Di, CPD and PF] have been identified having sig. ≤ 0.05, as revealed from Table 5.40. The results of the MLR for PPV prediction performed on the 12 identified parameters have been summarized in Table 5.41.

Table 5.41: MLR for predicting PPV using the identified 12 parameters

Model	R	R Square	Adjusted R Square	Significance level	Std. Error of the Estimate
1	0.897	0.804	0.746	0.00	0.319904

MLR analysis reveals multi-collinearity in 5 out of 12 parameters. The values of VIF for the 5 parameters, which revealed multi-collinearity, are tabulated in Table 5.42.

Table 5.42: Blast design parameters with multi-collinearity (VIF >10) for PPV (quarry C)

S.No.	Blasting design parameters	VIF values
1	B	11.25
2	T	19.36
3	S/B	14.85
4	Nh	18.25
5	PF	17.12

Consequently, after removal of 5 parameters exhibiting multi-collinearity, only the 7 parameters [H/B, T/CCL, Nr, Qe, CPD, Di, and S] identified having no multi-collinearity are summarized in Table 5.43.

Table 5.43: Blast design parameters without multi-collinearity (VIF <10) for PPV (quarry C)

S.No.	Blasting design parameters	VIF values
1	H/B	8.595
2	T/CCL	3.149
3	Nr	1.544
4	Qe	1.920
5	CPD	3.253
6	Di	1.155
7	S	1.202

As such, the unstandardized coefficients of the selected blasting design parameters together with their significance value and standard error are presented in Table 5.44. This table presents the unstandardized coefficients with the significance, standard error and collinearity statistics of the identified blasting design parameters.

Table 5.44: Descriptive statistics of 7 parameters for developing predictor Eq. for PPV

Blasting design parameters	Unstandardized Coefficients		Significance level	Collinearity Statistics	
	B	Std. Error		Tolerance	VIF
(Constant)	-.777	3.815	.839		
H/B	.044	.875	.782	.116	8.595
T/CCL	1.697	1.443	.244	.318	3.149
Nr	.459	.436	.297	.387	1.544
Qe	.004	.002	.819	.267	1.920
CPD	.002	.041	.626	.307	3.253
Di	-.002	.002	.000	.865	1.155
S	.096	.848	.910	.276	1.202

The developed model in the form of equation using unstandardized regression coefficient (β-value) associated with 7 retained PCs (as illustrated in Table 5.74), is presented in Eq.5.6:

$$PPV = -0.777 - \frac{H}{B} \times (0.044) + \frac{T}{CCL} \times (1.697) + Nr \times (0.459) + Qe \times (0.004) + CPD \times (0.002) - Di \times (0.002) + S \times (0.096) \qquad \mathbf{(5.6)}$$

The MLR analysis results for the developed equation has been presented in Table 5.45.

Table 5.45: MLR based descriptive statistics for the parameters used in Eq.5.6

Model	R	R Square	Adjusted R Square	Significance level	Std. Error of the Estimate	F
1	0.869	0.755	0.698	0.00	0.246236	21.536

A close perusal of the value of R^2 has been found 0.755 and adjusted R^2 has been found as 0.698. The F-ratio has been found to be 21.536, which is much greater than 4 and significance level has been found as 0.00, which improves the authenticity of the predicted equation.

Since the 7 parameters were introduced sequentially, Therefore it may be consequential to state that with the addition of each parameter, the value of R^2 increased from 0.308 to 0.755, as clearly revealed in Table 5.46.

Table 5.46: Summary of models prepared by MLR using SSE for PPV (quarry C)

Model	R	R Square	Adjusted R Square	Significance level	F	Predictor constants
1	0.555	0.308	0.261	0.002	11.234	H/B
2	0.616	0.379	0.325	0.005	13.025	H/B+T/CCL
3	0.658	0.432	0.384	0.002	13.265	H/B+T/CCL+Nr
4	0.729	0.531	0.465	0.000	15.245	H/B+T/CCL+Nr+Qe
5	0.749	0.561	0.507	0.000	19.125	H/B+T/CCL+Nr+Qe+CPD
6	0.798	0.636	0.576	0.000	19.365	H/B+T/CCL+Nr+Qe+CPD+Di
7	**0.869**	**0.755**	**0.698**	**0.000**	21.536	H/B+T/CCL+Nr+Qe+CPD+Di+S

5.4 Results of validation and verification

Validation and verification section comprises two part, one is validation and another is verification.

5.4.1 Validation results

The validation of the developed equation with the different data set of the corresponding quarries has been done within statistical domain. The data set for validation and are illustrated in Appendix-A.4, A.5 and A.6. The results of this validation are described in the following sections:

(i) Results of validation of developed equation for the PPV (Quarry A)

The results of computed values of PPV by PCA, SSE and Square root equation methods are distinctly illustrated in form of bar chart (Figure 5.4).

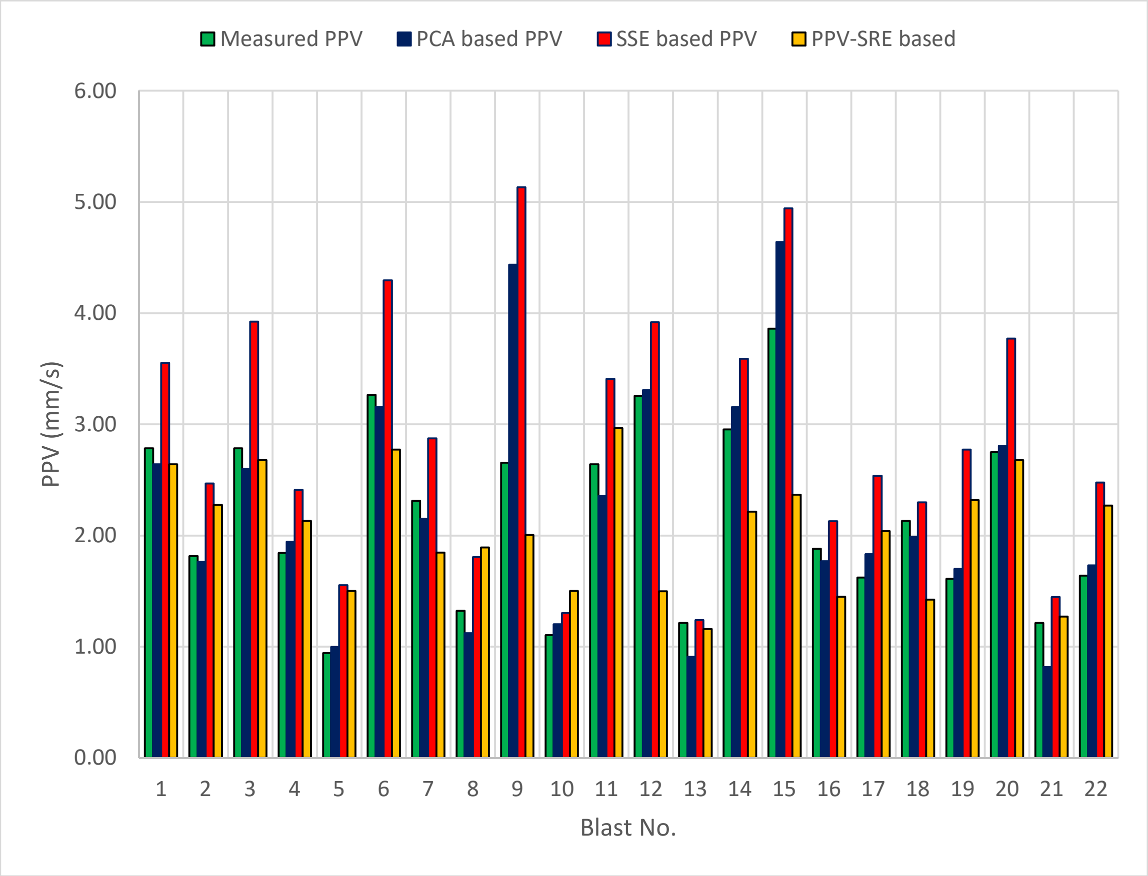

Figure 5.4: Comparison of measured and predicted PPV values for quarry A

The value of PPV obtained using PCA equation lies between 0.99mm/s – 4.61mm/s for distances varying from 250m – 400m. Whereas, the values of PPV obtained using SSE equation and square root equation lies between 1.30 mm/s – 5.31mm/s and between 1.16 mm/s – 2.97 mm/s respectively for the same range of measuring distance.

The average standard deviations for the predicted values of PPV using PCA analysis has been found to be 0.13. However, for SSE and SRE techniques, the average standard deviation has found to be 0.37 and 0.26 respectively, which is higher than that of PCA.

Therefore, the values obtained by the PCA equation are more precise as compared to the SSE and SRE techniques. This in turn, validates the precision of the developed equation using PCA, and this validation has set a high level of statistical assurance on the predictor Eq. 5.1 for the given study quarry.

(ii) Results of validation of the developed equation for the PPV (Quarry B)

The results of computed values of PPV by PCA, SSE and square root equation methods are distinctly illustrated in form of bar chart (Figure 5.5).

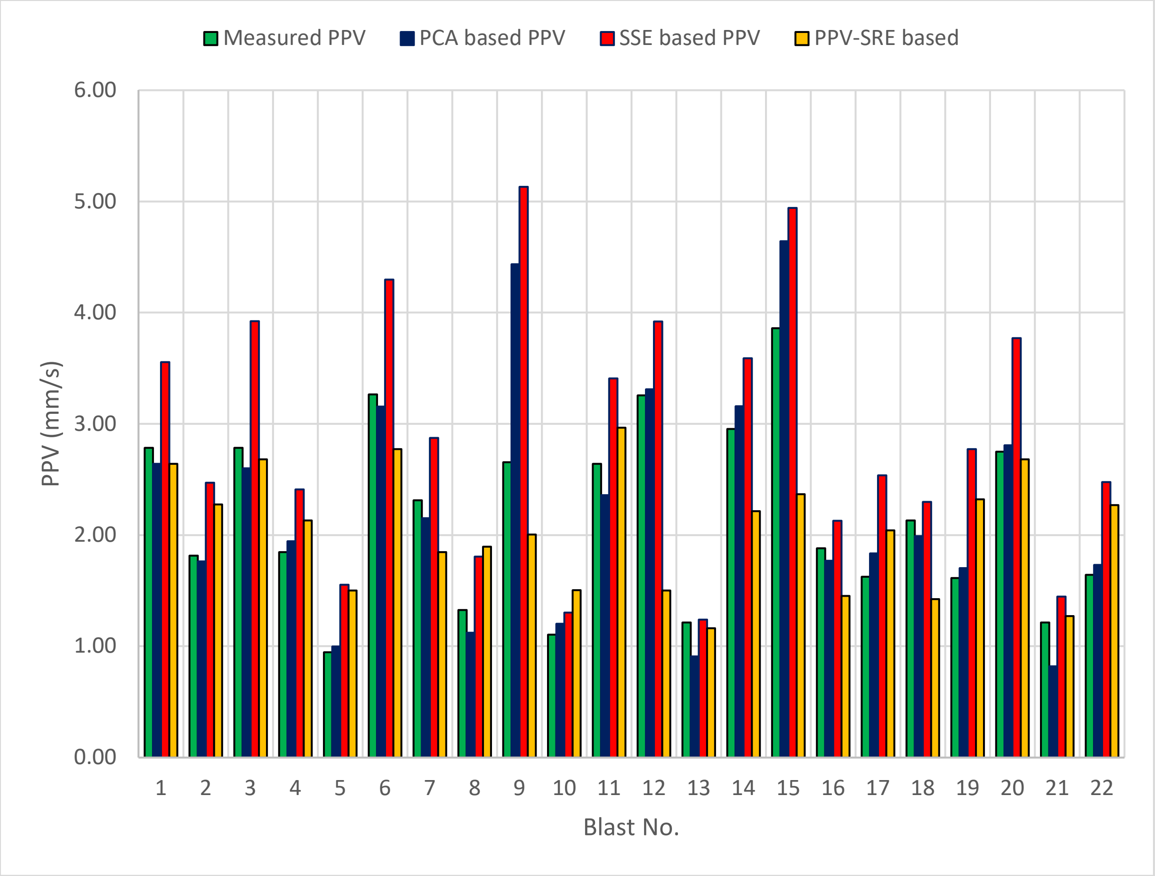

Figure 5.5: Comparison of measured and Predicted PPV Values for quarry B

The value of PPV obtained using PCA equation lies between 1.31 mm/s – 3.84 mm/s for distances varying from 150m – 320m. Whereas, the values of PPV obtained using SSE equation and square root equation lies between 1.86 mm/s – 3.88mm/s and between 0.75 mm/s – 3.17 mm/s respectively for the same range of measuring distance.

The average standard deviations for the predicted values of PPV using PCA analysis has been found to be 0.17. However, for SSE analysis and SRE, the average standard deviation has been found to be 0.45 and 0.30 respectively, which is higher than that of PCA. Therefore, the values obtained by the PCA equation are more precise as compared to SSE and SRE techniques. This in turn, validates the precision of the developed equation using PCA, and this validation has set a high level of statistical assurance on the predictor Eq. 5.5 for the given study quarry.

(iii) Results of validation *of developed equation for the PPV (Quarry C)*

The results of computed values of PPV by PCA, SSE and Square root equation methods are distinctly illustrated in form of bar chart (Figure 5.6).

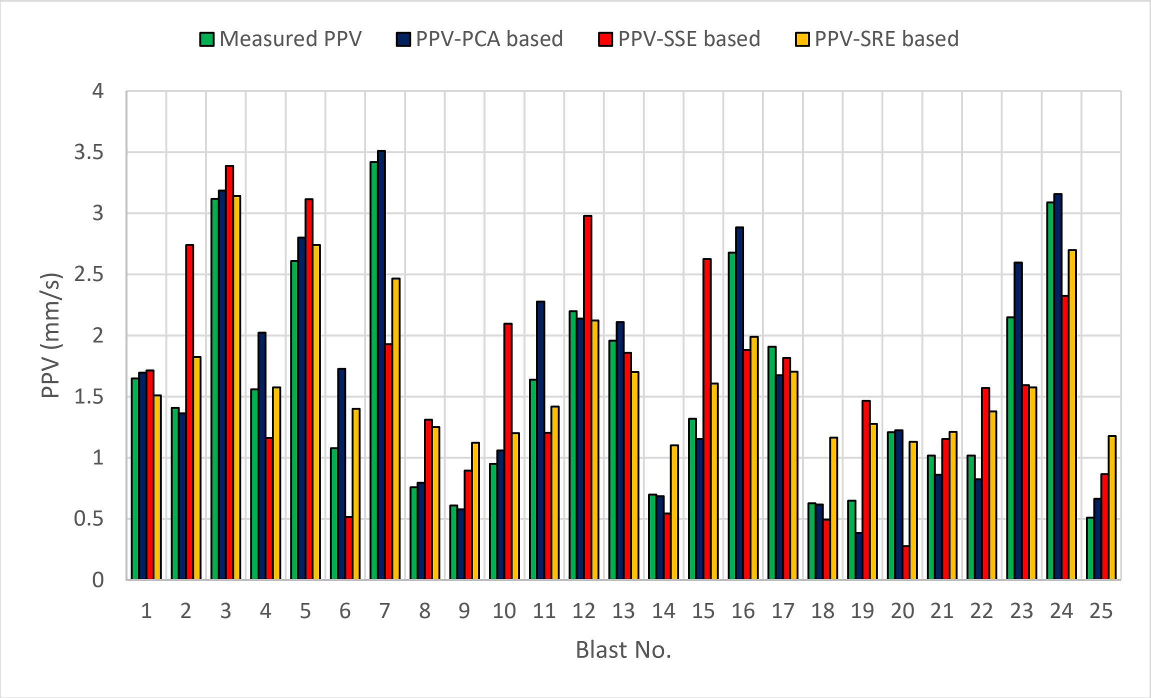

Figure 5.6: Comparison of measured and predicted PPV values for quarry C

The value of PPV obtained using PCA equation lies between 0.70mm/s – 3.51mm/s for distances varying from 200m – 500m. Whereas, the values of PPV obtained using SSE equation and square root equation lies between 0.52 mm/s – 3.39mm/s and between 1.10 mm/s – 3.14 mm/s respectively for the same range of measuring distance.

The average standard deviations for the predicted values of PPV using PCA analysis has been found to be 0.09. However, for SSE analysis and SRE, the average standard deviation has been found to be 0.29 and 0.18 respectively. which is higher than that of PCA. Therefore, the values obtained by the PCA equation are more precise as compare to SSE and SRE equation. This in turn, validates the precision of the developed equation using PCA, and this validation has set a high level of statistical assurance on the predictor Eq. 5.9 for the given study quarry.

5.4.2 Verification

Verification has been carried out outside the statistical domain, using A.I. tools, the multi-layer perceptron based ANN technique for further validating the blasting design results already validated in internal validation. This external validation aims at doubly ascertaining the authenticity of results by using state-of-art technique of ANN.

(i) Multilayer perceptron model (ANN) for verification of PPV (Quarry A)

To carry out the MLP neural network analysis, eleven parameters were selected which has been identified using PCA and SSE techniques. The parameters identified are Burden (B), Spacing (S), Stemming (T), Column charge length (CCL), Spacing/Burden ratio (S/B), Stemming/Burden ratio (T/B), No. of rows (Nr), Total amountof explosive (Qe), Distance (Di), Charge Per Delay (CPD) and Scaled distance (SD). These parameters have been feed as input parameters and PPV as output.

The network topology to predict the outcome (PPV), consists of three layer (Input, hidden and output layer). In the input layer, there are eleven input neurons, in the hidden layer, there are four neurons and one output neurons. The value of coefficient of determination (R^2) which was closer to 1 was found to be best one as such, high degree of correlation between blasting design parameters and PPV as well as PF indicates good predictability.

The model summary indicated in Table 5.47, provides information related to the results of training and testing samples. Sum of square error is given for both training and testing sample. The small value (3.121) of the error related to training sample indicates the power of the model to predict the outcome. According to the Table 5.47, the Sum of square errors is 3.121 for training and 2.704 for testing samples.

Table 5.47: Model summary for PPV using ANN (quarry A)

Model Summary of MLP		
Training	Correlation value	0.819
	Sum of Squares Error	3.121
	Relative Error	.118
	Stopping Rule Used	1 consecutive step(s) with no decrease in error
	Training Time	0:00:00.04
Testing	Correlation value	0.827
	Sum of Squares Error	2.704
	Relative Error	.438

The graph between measured value of PPV and predicted value by ANN technique has been plotted as shown in Figure 5.7. The value of coefficient of determination (R^2) was found to be 0.828, which indicates the high degree of correlation of the blasting design parameters with the PPV.

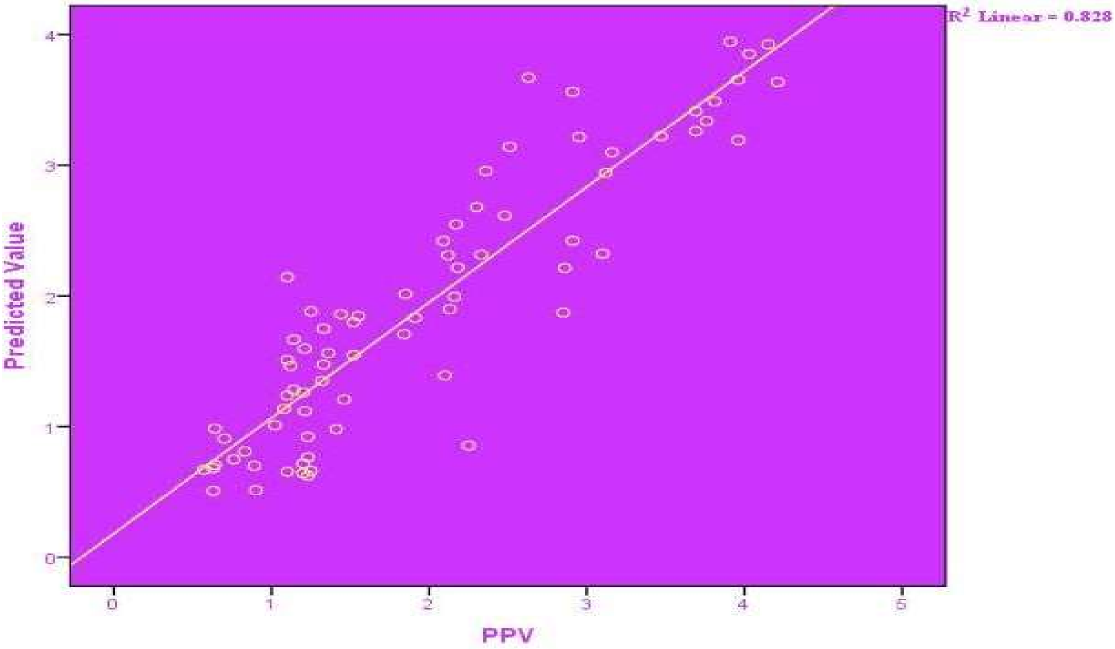

Figure 5.7: Plot between measured and predicted PPV by ANN (quarry A)

The MLP neural network model also gives the information about the impact of each independent variable in terms of normalized importance. The variable importance indicates the percent improvement with respect to the most important predictor. It has been calculated by dividing each variable score by the largest variable score, then multiply by 100%. For the calculation of variable importance, the relative importance criteria and the highest correlated parameters has been used.

Figure 5.8 illustrates the importance of the parameters.

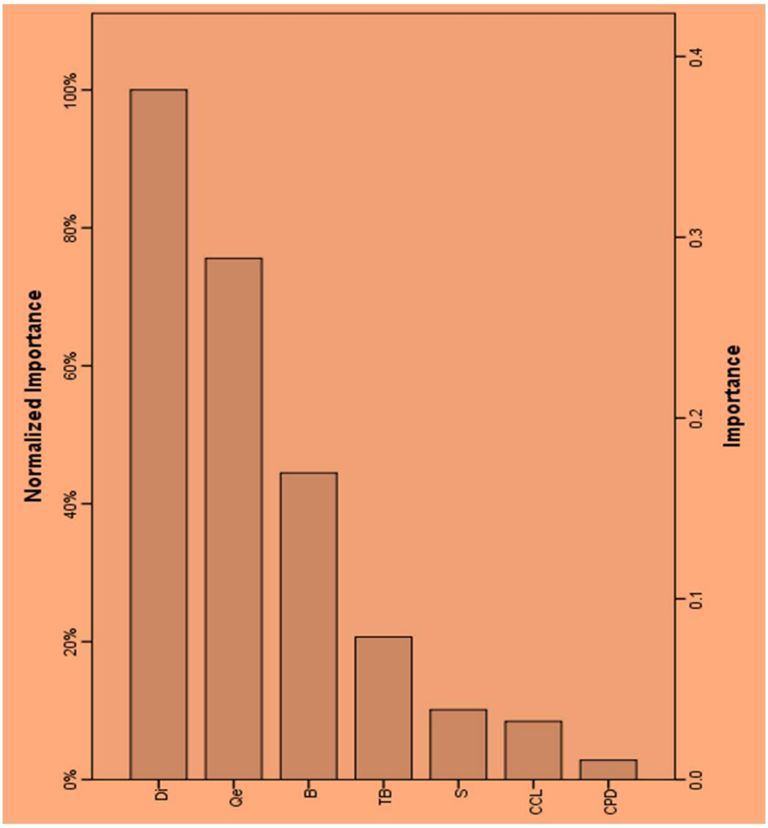

Figure 5.8: Independent variables importance chart for PPV (quarry A)

It is evident from the Figure 5.8, that in MLP technique, the most significant parameter is Di (Distance) with 100% influence. The other six parameters, namely, total amount of explosive (Qe), burden (B), stemming/ burden ratio (T/B), spacing (S), column charge length (CCL) and charge per delay (CPD) has been affecting the PPV in extent to 73%, 42%, 20%, 15%, 14% and 4% respectively.

(ii) Multilayer perceptron model for verification of PPV (Quarry B)

To carry out the MLP neural network analysis, eleven parameters were selected which has been identified using PCA and SSE techniques.

The parameters identified are Burden (B), Spacing (S), Spacing/Burden ratio (S/B), Stemming/Burden ratio (T/B), Stemming/Column charge length ratio (T/CCL), No. of holes (Nh), Total amount of explosive (Qe), Distance (Di), Charge Per Delay (CPD), Scaled distance (SD) and Row delay (RD)

The network topology to predict the outcome (PPV), consists of three layer (Input, hidden and output layer). In the input layer, there are eleven input neurons, in the hidden layer, there are four neurons and one output neurons. The model summary indicated in Table 5.48, provides information related to the results of training and testing samples. Sum of square error is given for both training and testing sample. The small value (2.580) of the error related to training sample indicates the power of the model to predict the outcome. According to the Table 5.48, the Sum of squared errors is 3.518 for training and 2.580 for testing samples.

Table 5.48: Model summary for PPV using ANN (quarry B)

Model Summary for MLP		
Training	Correlation value	0.906
	Sum of Squares Error	3.518
	Relative Error	.130
	Stopping Rule Used	1 consecutive step(s) with no decrease in error
	Training Time	0:00:00.04
Testing	Correlation value	0.926
	Sum of Squares Error	2.580
	Relative Error	.343

The graph between measured value of PPV and predicted value by ANN technique has been plotted as shown in Figure 5.9. The value of coefficient of determination (R^2) was found tobe 0.926, which indicates the high degree of correlation of blasting design parameters with the PPV.

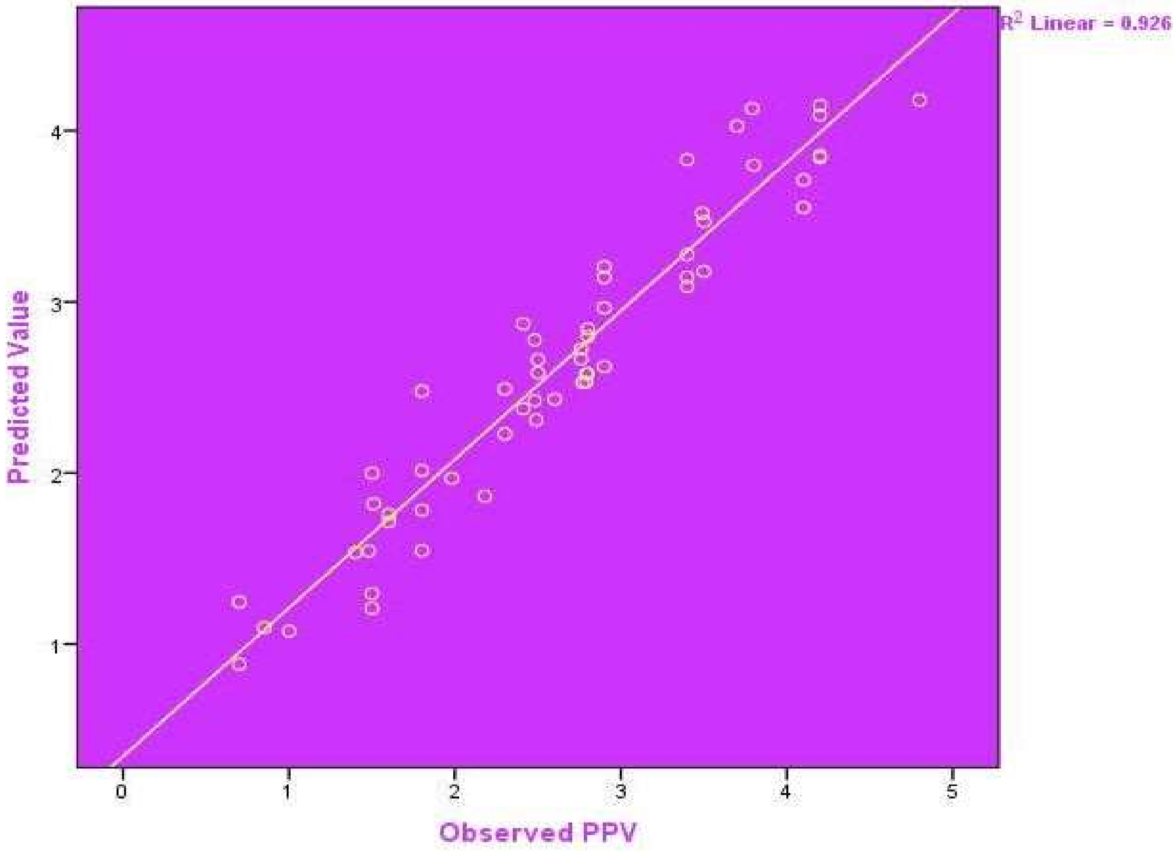

Figure 5.9: Plot between measured and predicted PPV by ANN (quarry B)

The MLP neural network model also gives the information about the impact of each independent variable in terms of normalized importance. Figure 5.10 indicates the importanceof the variables.

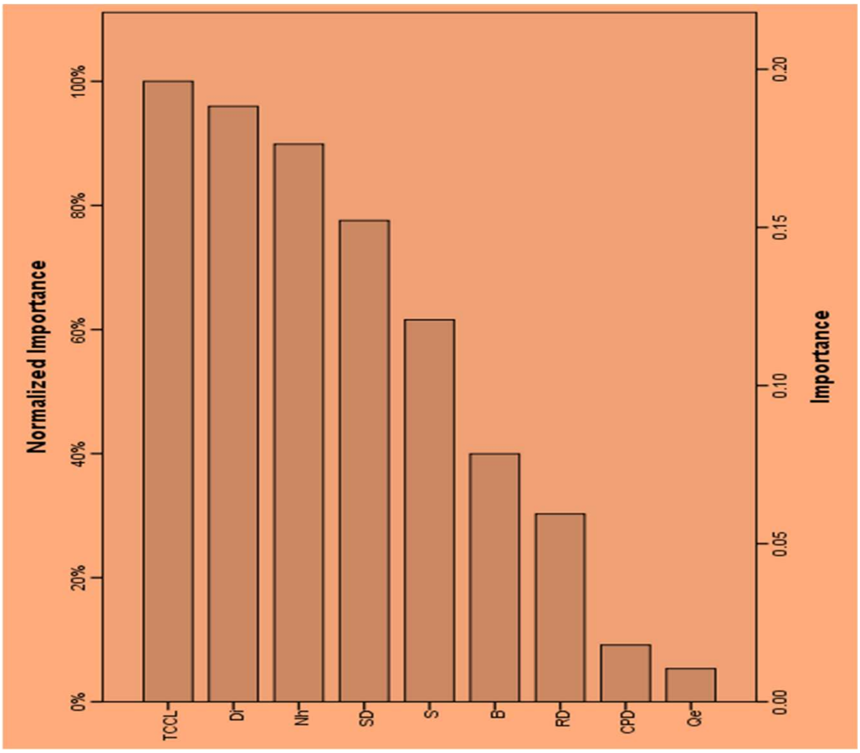

Figure 5.10: Independent variables importance chart for PPV (quarry B)

It is evident from the Figure that in MLP technique, the most important parameter is T/CCL (stemming/column charge length) with 100% influence on PPV. Three parameters, namely, Di, Nh and SD affecting PPV in extent for 98%, 95% and 78% respectively. The five parameters namely, S, B, RD, CPD and Qe have been affecting the PPVwith extent to 60% , 40%, 35%, 9% and 5% influence.

(iii) Multilayer perceptron technique for verification of PPV (Quarry C)

To carry out the MLP neural network analysis, fourteen parameters were selected which has been identified using PCA and SSE techniques. The parameters identified are Total amount of explosive(Qe), No. of holes (Nh), Column charge length (CCL), Charge per delay (CPD), Hole depth (H), Diameter of hole (D), Scaled distance (SD), Spacing/burden ratio (S/B), Burden (B),Hole depth/Burden ratio (H/B), Spacing (S), Stemming/charge column length (T/CCL), Distance (Di) and Number of rows (Nr).

The network topology to predict the outcome (PPV), consists of three layer (Input, hidden and output layer). In the input layer, there are fourteen input neurons, in the hidden layer, there are five neurons and one output neurons. The model summary indicated in Table 5.49, provides information related to the results of training and testing samples. Sum of square error is given for both training and testing sample. The small value (6.399) of the error related to training sample indicates the power of the model to predict the outcome. According to the Table 5.49, the Sum of squared errors (SSE) is 6.399 for training and 3.651 for testing samples.

Table 5.49: Model Summary foe PPV using ANN (quarry C).

Model Summary for MLP		
Training	Correlation Value	0.864
	Sum of Squares Error	6.399
	Relative Error	.272
	Stopping Rule Used	1 consecutive step(s) with no decrease in error
	Training Time	0:00:00.02
Testing	Correlation Value	0.878
	Sum of Squares Error	3.651
	Relative Error	.479

The graph between measured value of PPV and predicted value by ANN technique has beenplotted as shown in Figure 5.11. The value of coefficient of determination (R^2) was found to be 0.879, which indicates the high degree of correlation of independent parameters with the PPV.

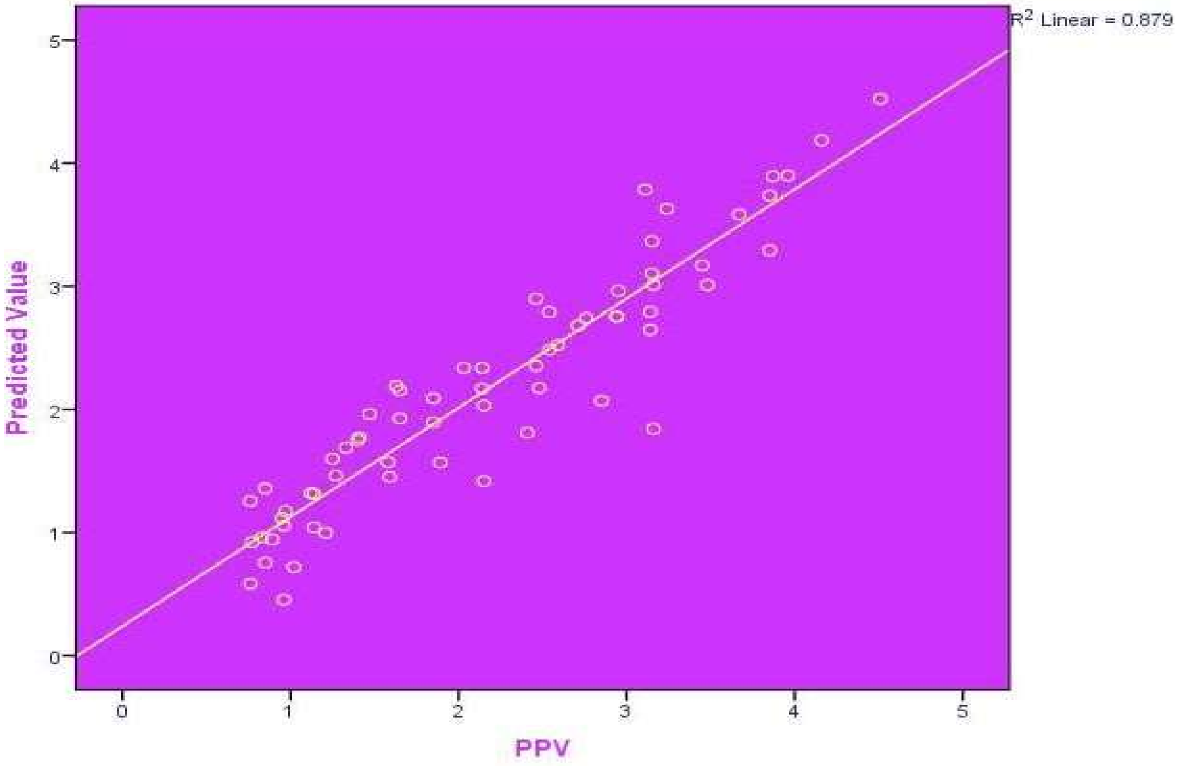

Figure 5.11: Plot between measured and predicted PPV by ANN (quarry C)

The MLP neural network model also gives the information about the impact of each independent variable in terms of normalized importance. Figure 5.12 indicates the importanceof the variables.

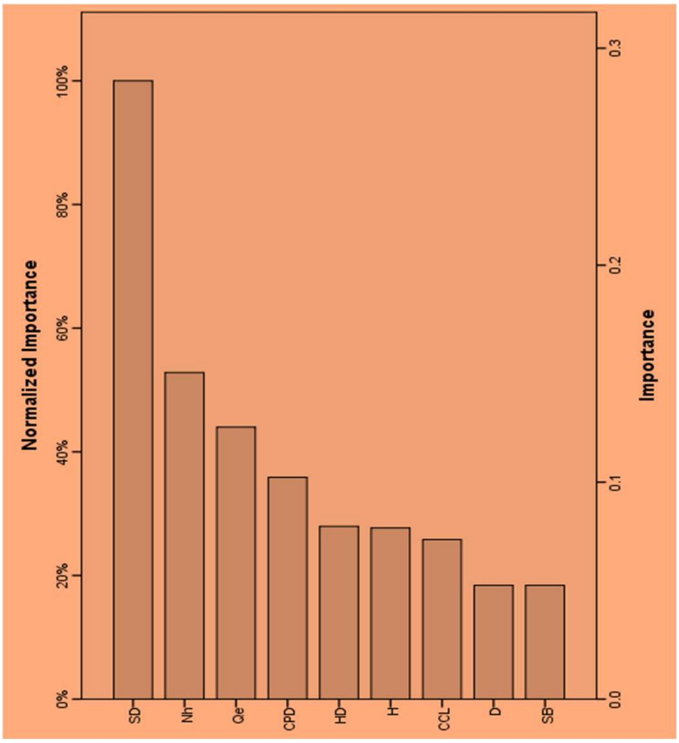

Figure 5.12: Independent variables importance chart for PPV (quarry C)

It is evident from the figure that in MLP technique, the most important parameter is SD (Scaled distance) with 100% influence on PPV. Eight parameters, namely, Nh, Qe, CPD, HD, H, CCL, D, S/B have been affecting PPV in extent to 52%, 43%, 38%, 35%, 35%, 34%, 18% and 18 % respectively.

5.5 Discussion

For quarry A, PCA has selected eight blasting design parameters namely, Di, CCL, B, Qe, CPD, S and T/B and SSE have selected seven blasting design parameters namely, SD, S/B, T, Qe, Nr and Di, which have major impact on PPV. The value of R^2 is found to be 0.74 for PCA and 0.68 for SSE. However, the square root equation includes only Di (distance) and Qe (amount of explosive) to predict the PPV.

For quarry B, the PCA has selected 9 blasting design parameters namely, Nh, RD, T/CCL, Di, B, SD, CPD, Qe and S and SSE has selected 6 blasting design parameters namely, S/B, T/CCL, Nh, CPD, SD and Qe, which have major impact on PPV. The value of R^2 is found to be 0.81 for PCA and 0.75 for SSE.

For quarry C, the PCA has selected 9 blasting design parameters namely, H, D, HD, SD, Nh, S/B, Qe, CCL and CPD and SSE has selected 7 blasting design parameters H/B, T/CCL, Nr, Qe, CPD, Di, and S, which affect the PPV. The value of R^2 for PCA and SSE was found to be 0.82 and 0.76 respectively. PCA has the high level of statistical assurance as compare to SSE.

On validation within the statistical domain, for PPV in all the quarries, the predicted values of PPV are lying closer to the measured values. But, the values predicted by PCA reveals the most accurate values of PPV comparison to SSE and SRE.

Apart from the statistical domain, ANN (Multilayer Perceptron) technique has also been used to verify the equation developed by both PCA and SSE tools and also to determine the correlation between the blasting design parameters with PPV. It has been found that the value of R^2 derived by ANN is much higher than the values of R^2derived by both PCA and SSE. This indicates that the accuracy of ANN in predicting PPV is very much satisfactory in comparison to PCA and SSE, and doubly validate the authenticity of equation developed by PCA and SSE in predicting the PPV. However, PCA and SSE have also indicated the excellent value of R^2 vis-à-vis better authenticity of the equation to predict both PPV.

5.5.1 Identified blasting design parameters affecting PPV by PCA and SSE

PCA and SSE techniques has identified some blasting design parameters affecting Peak particle velocity and the coefficient obtained for the selected parameters are both positive and negative. The explanation of selected parameters is given below:

(i) Burden- The coefficient related to burden (B) is found positive by both PCA and SSE. As we increase the burden, the explosive required to break the rock mass will increase. If we increase the burden with same explosive quantity, then it will increase the level of ground vibration. Bilgin et al.,(1997) also found the similar kind of relation.

(ii) Stemming (T)- The main objective of stemming is to confine the explosive gasses, so that they have enough time to fracture the ground. The coefficient related to stemming (T) is found positive by both PCA and SSE. So, if the stemming is increased then it will increase the level of ground vibration. Hagan and Kennedy (1998), also reported a similar relation and said that, a stemming length, may enhance the ground vibrations due to long confinement and high pressure, developed in boreholes. This condition limits the rock deformation and restricts the propagation of fractures, which in turn leads to enhanced ground vibration.

(iii) Total amount of explosive (Qe)- The coefficient related to total amount of explosive (Qe) is found positive by both PCA and SSE. This indicates that, if the Qe is increased then it will increase the level of ground vibration. Singh et al. (2005) also reported a similar relation that the total charge in a blast round affects the ground vibration at distances close to the blast and its effect diminishes quickly with distance.

(iv) Column charge length (CCL)- The coefficient related to column charge length (CCL) is found positive by both PCA and SSE. It will lead to increase in total amount of explosive and subsequently leads to increase in blast induced ground vibration.

(v) Number of holes (Nh)- The coefficient related to Nh is found positive by both PCA and SSE resulting in more quantity of explosive. Due to this, higher proportion of explosive energy will translate into seismic waves leading to increase in PPV. However, effective delay pattern can minimize the effect of number of holes on ground vibration.

(vi) Charge per delay (CPD)- The coefficient related to CPD is found positive by both PCA and SSE. Nichols et al. (1971) also reported that the ground vibration characteristics depends on maximum charge per delay for any delay interval, instead of total explosive blasted. Hence, with increase in CPD the ground vibration levels also increase.

(vii) Height/Burden (H/B)- The coefficient related to H/B is negative. When H/B ratio is high, the bench becomes less stiff, more flexible and less resistant to breakage. This is due to the increase in the bench height for a given value of burden resulting in decreasing intrinsic rock strength and better rock breakage. Subsequently leading to decrease in the level of ground vibration.

(viii) Stemming/Column charge length (T/CCL)- The coefficient related to T/CCL is found positive by both PCA and SSE. When CCL increases and stemming remain same, it will lead to increase in the amount of explosive and subsequently, blast induced ground vibration will increase. When Stemming increases, it may enhance the ground vibrations due to long confinement and high pressure developed in boreholes. So, it is interesting to maintain the T/CCL ratio in such a way that the induced ground vibration can be controlled.

(ix) Distance (Di)- The coefficient related to Di is found negative by both PCA and SSE. So, as the distance of measuring point of PPV increases, the propagation of waves get diminishes. This leads to decreases in the value of PPV and subsequently decrease in level of ground vibration.

(x) Scaled distance (SD)- The coefficient related to SD is found negative by both PCA and SSE. The USBM equation also proposes a similar relation between PPV and Scaled distance. It is also verified by our prediction that the PPV decreases with increase in the SD.

(xi) Row delay and Hole delay- The coefficient related to RD and HD is found negative by both PCA and SSE. Delay interval is the lag in firing timing between two consecutive detonations in blasting round. Hoshino et al., (2000) reported that, vibration waves, emitted from the blast holes, interfere with each other and the Peak Particle Velocity (PPV) of the ground vibration caused by the integrated wave at a certain point of interest could be reduced by using proper time intervals. Therefore, it is also verified by our prediction that the PPV decreases with increase in the delay intervals.

(xii) Spacing- The coefficient related to S is found negative by both PCA and SSE. The spacing can further have increased to minimize the ground vibration levels. However, PPV was found to be within limits in all the blasts as per DGMS circular. By increasing the spacing of blast holes, the chances of superimposition of colliding waves from the surrounding holes reduces, thereby reducing the ground vibration levels, which verify the proposed equation.

5.6 Overview of the results for all the three quarries

The results obtained for all the quarries using statistical (PCA, SSE and SRE) and ANN technique, in terms of blasting design parameters, R^2 and root means square error (RMSE), are summarized in Table 5.50.

Table 5.50: Results at a glance for PPV (Quarry A, B and C)

For prediction of PPV									
Methods	Quarry A			Quarry B			Quarry C		
	Equation developed by the statistical technique	R^2 value	RMSE	Equation developed by the statistical technique	R^2 value	RMSE	Equation developed by the statistical technique	R^2 value	RMSE
PCA	$PPV = 0.645 - S \times (1.022) + \frac{T}{B} \times (1.016) + Qe \times (0.001) + CPD \times (0.012) + B \times (0.591) + CCL \times (0.133) - Di \times (0.008)$	0.74	0.991	$PPV = 5.379 + Nh \times (0.002) - RD \times (0.013) + \frac{T}{CCL} \times (0.951) - Di \times (0.014) + B \times (1.799) - SD \times (0.231) + CPD \times (0.068) + Qe \times (0.002) - S \times (1.489)$	0.81	0.986	$PPV = -0.391 + Nh \times (0.136) + Qe \times (0.003)) + CCL \times (0.111) + CPD \times (0.062) + H \times (0.381) - D \times (0.032) - SD \times (0.051) + \frac{S}{B} \times (2.281) - HD \times (0.105)$	0.82	0.926
SSE	$PPV = -2.431 + T \times (0.358) + \frac{S}{B} \times (2.105) + Nr \times (0.074) + Qe \times (0.001) - Di \times (0.005) - SD \times (0.020)$	0.68	1.087	$PPV = 11.480 - \frac{S}{B} \times (1.312) + \frac{T}{CCL} \times (1.975) + Nh \times (0.019) + CPD \times (0.017) - SD \times (0.127) + Qe \times (0.002)$	0.75	1.049	$PPV = -0.777 - \frac{H}{B} \times (0.044) + \frac{T}{CCL} \times (1.697) + Nr \times (0.459) + Qe \times (0.004) + CPD \times (0.002) - Di \times (0.002) + S \times (0.096)$	0.76	1.052
SRE		0.72	1.017		0.78	1.041		0.77	1.042
ANN	Parameters of PCA and SSE both	0.83	0.314	Parameters of PCA and SSE both	0.92	0.212	Parameters of PCA and SSE both	0.88	2.84