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Article

New Approach for Identification of Suitable Vibration Attenuation Relationship for Underground Blasts

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Abstract. For construction and mining activities, excavation is often performed with the help of blasting in hard or weathered rock or even hard soil. As a safety practice, the blasting operation is designed so that the nearby structures are not adversely affected. For this, blast vibration attenuation relationship for the ground media becomes necessary. In India, the relevant IS code specifies an attenuation relationship (Power expression) between the peak particle velocity, the charge weight and the distance of the monitoring point from the blast. However, the empirical coefficients are provided in IS code for only two categories - hard rock and weathered rock / soil. Hence they result in uneconomical and sometimes unviable blasting design. In lieu of above, site specific attenuation relationship may be used for design of blasting operation. Industrial practice is to find the empirical constants for the same Power expression (as IS code) using trial blast data from the site. For this purpose, the same dataset is used for parameter estimation as well as evaluation of the suitability of the estimated parameters. In this study it is demonstrated that evaluation of performance with a different dataset alters the conclusions. Further, expressions other than the commonly adopted Power expression might be more suitable for the relationship. In this article, two other expressions, namely, Reciprocal expression and Weibull model were identified which could be equally good. Exponents for scaled distance calculation, other than the popularly adopted 0.5, were found to be applicable in the case study. Trail blast data from a site was used to demonstrate the same.

It was concluded that while developing site specific attenuation relationship, various expressions with different exponents should be examined for their suitability. The available dataset should be split into parameter estimation set and performance evaluation set. The best expression identified for the site from the performance evaluation set should be finally adopted for further activities.

Keywords: Underground blast, peak particle velocity, attenuation relationship, power law, reciprocal law, Weibull model.

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1. Introduction

For construction and mining activities, blasting in weathered and hard rock is preferred to other methods like mechanical chiseling mainly due to the ease of excavation and the speed of execution. The savings in terms of the time schedule largely offsets the additional expenses incurred for the blasting studies, actual blasting operation and monitoring. A part of the energy released by blasting is expended to fragment the surrounding rock and some part is always exhibited in the form of elastic waves radiating from the blasting source [1]. These shock waves travel in all directions and give rise to ground vibrations, which in excess might cause distress or damage to surrounding structures [2, 3, 4]. This is a major concern area in case of blasting activity near important structures, vintage structures and strategic structures.

The transmission and attenuation of the vibrations induced by the blasting is a complex phenomenon influenced by many variables such as the charge weight, the depth of blasting, and the soil / rock properties among others. As a safety practice the blasting operation has to be designed such that the surrounding existing structures are not adversely affected due to the blasting activity. The regulatory agencies fix up the guidelines such that the different structures around the blasting site are protected according to their importance, age, etc. The concerns of occupants of the surrounding buildings are generally how much the buildings shake due to the blasting activity. There are three factors of ground vibration which helps quantification of the effect of the blasting and degree of shaking: ground vibration amplitude or peak particle velocity (PPV), its duration and frequency [5]. Of these, the PPV is taken as a variable for fixing up the statutory guidelines. For any blasting operation, the regulatory requirement is that the blasting activity should be monitored at different locations and distances to ensure that the actual PPV remains less than the permissible one.

In addition to the variable PPV, the frequency content and the relative amplitude of horizontal and vertical components may influence the response of structures due to blasting in the nearby areas. There are many other variables such as the charge loading density, site geology, blast geometry which would affect the structural response to blasting [6]. It has been observed that the rock damage extent around the tunnels and other structures linearly increases with the PPV [7]. Studies have shown that human beings notice and react to vibration at levels much lower than the levels established as structural damage thresholds [8, 9]. Previous studies on human response to transient vibrations have established that human tolerance to vibration decreases the longer the vibration continues [10]. The PPV had been reported [11] as a good indicator of the degree of damage to structures caused by blasting.

In industrial practice as well as in researches, the Power form of the expression with '*n*' as 0.5 has been preferred for the attenuation relationship for underground blasts, viz. Istanbul Kadıköy–Kartal metro tunnel [12, 13]; for dredging operation in Mumbai Port Trust and the safety of the Elephanta Caves [14]; a 85 year old masonry dam and fresh concrete structures [1]; and underground mine blasting [10, 15]. Application of soft computing techniques like artificial neural network (ANN) had been reported for estimation and prediction of PPV for underground blasts. A study [16] was conducted wherein ANN was employed to accurately predict the ground vibration and frequency taking into consideration the various influencing factors such as rock mass, explosive characteristics and blast design. Other works directed towards application of ANN for blast effect prediction dealt with blasting for coal mines in India [17], copper mines in Iran [18], open-pit mines [19].

From the foregoing discussion it is evident that the Power form of expression has been extensively used with an exponent (n) of 0.5 in numerous blasting studies and site specific attenuation relationships were established for each case. IS standard also proposes the same expression with the exponent (n) being defined as 0.667 [20] or suggested to be fixed up by curve fitting between 0.4 and 0.6 [21]. Generally, the suggested approach is to use a data subset for estimation of empirical model parameters and evaluate the performance of the model with the conjugate subset. However, it is observed that in literature dealing with empirical vibration attenuation relations for underground blasts, the common practice adopted is using the total available dataset for estimation of the parameters of expression as well as performance evaluation. Selection of site specific vibration equation had been reported for a quarry wherein analytical hierarchy process was employed [22]. Further studies for selection of attenuation relationship for underground blasts in rock / hard soil are scarce in literature. At this backdrop, the objectives of the present study are identified as follows:

(1) To examine whether expressions other than the predominantly used Power form would be suitable for attenuation relationship for underground blasts.

(2) To explore exponents other than the industrial practiced value of 0.5 or the IS code specified value of 2/3 would be suitable for attenuation relationship for underground blasts.

(3) To check whether the practice of using the entire dataset for estimation of empirical parameters as well as evaluation of performance affects the final outcome, when compared to the proposed approach of using a data subset for estimation of parameters and the conjugate subset for evaluation of performance.

After introduction to the topic in this section, the data and methodology will be discussed in Section 2. The results obtained in the study would be presented along with discussions on the same in Section 3. The study will be summarized in Section 4, which will be followed by acknowledgements and list of references.

2. Data and Methodology

2.1. Theoretical Background

The general methodology adopted for safe blasting operation involve setting a safe vibration level that a structure could withstand without producing any damage, establishing attenuation relations describing propagation characteristics of blast vibrations, estimation of safe charge weight per delay for different distances, optimization of the blasting pattern used for rock excavation based on field trials and vibration monitoring during the actual blasting operation [1]. Adoption of this general methodology help to ensure the structural safety of engineered structures such as bridges, dams, and power plants, residential and commercial buildings in urban and rural areas, as well as historical monuments while blasting operation is carried out in adjacent construction projects.

In blasting studies, an independent variable is defined as 'scaled distance' and the attenuation relationship of the PPV is developed as a variable dependent of the scaled distance. The scaled distance (*X*) is generally the ratio of distance (*D*) in metres (or m) raised to an exponent (*n*) of the charge per delay (*Q*) in kilograms (or kg) as given in Eq. (1).

$$X = \frac{D}{Q^n} \quad (1)$$

Indian standard [20] provides some guideline regarding the relationship between the *PPV* and the scaled distance in the Power form Eq. (2) and suggests an exponent '*n*' of 2/3 for evaluation of the scaled distance in Eq. (1).

$$PPV = a\,X^b \quad (2)$$

where, *a, b*: empirical constants.

Another IS code [21] suggests fixing the exponent by curve fitting between values of 0.4 and 0.6. The basic assumption in Eq. (2) is that the explosive column is considered as a point charge considering the distance is much more as compared to explosive column length [23]. This assumption is not valid for near-field measurements and a mathematical model was proposed for accounting for the effect of the finite dimensions of the explosive column depth [23].

Indian code [20] stipulates a value of (-1.25) for '*b*' and gives only two values of '*a*': 880 for soft / weathered rock and soils; 1400 for hard rock where *PPV* is in mm/sec, *Q* is in kg, *D* is in metres. These are very generic values and are deemed to yield safe charge weights for blasting in any part of the country, irrespective of the particular type of rock, local geology and other factors. Thus using IS code attenuation relationship in most cases result in over conservative values of charge weight. This would make the blasting activity expensive in terms of money and time both, and may even make the activity unviable from practical considerations. Though the IS code relationship [20] may be used to set up the blast design, in most cases, site specific attenuation relationships are developed based on trial blast data, which may be designed based on the IS code [20].

A study set up guidelines for the safe PPV limits for residential structures based on extensive blasting and building response experimentation and analysis [24]. The limits were set in year 1985 as 19.05 mm/sec to 50.8 mm/sec for modern structures and 12.7 mm/sec for old structures. Advent of concrete structures has induced upward revision of the aforementioned limits on PPV for safe underground blasting activity. The damage threshold values of PPV is given by IS code [20] for hard rock is 70 mm/sec and for soft / weathered rock and soil is 50 mm/sec as evaluated from the IS code relationship. In cases where monitoring of the blasting activity is carried out according to the relevant IS code [21], the corresponding values are stipulated as 100 mm/sec for hard rock and 70 mm/sec for soft / weathered rock and soil. For ancient national monuments and vintage structures, the PPV limit is 15 mm/sec [21]. For sensitive or important installations like power plants and bridges, more stringent limits on the PPV would be adopted. For green concrete the safe PPV limits are based on the age: for example, in one case, the limits were set as 3 mm/sec for age up to 12 hours, 10 mm/sec beyond 12 hours till 24 hours, and 15 mm/sec beyond one day till three days and so on.

2.2. Data

The data available for the study were the records of trial blasting at a basaltic rocky site in the western coastal region in India. The variables which were recorded included:

a) Maximum charge per delay (in kg);
b) Distance between the blasting point and instrument location (in m);
c) Observed PPV at the instrument station in mm/s for different combinations of the charge per delay and distances.

The blast vibrations at different distances for the respective charge weights were measured with three component seismographs (DS-077 from M/s Instantel Inc., Canada, Fig. 1) which were pre-calibrated at laboratory.

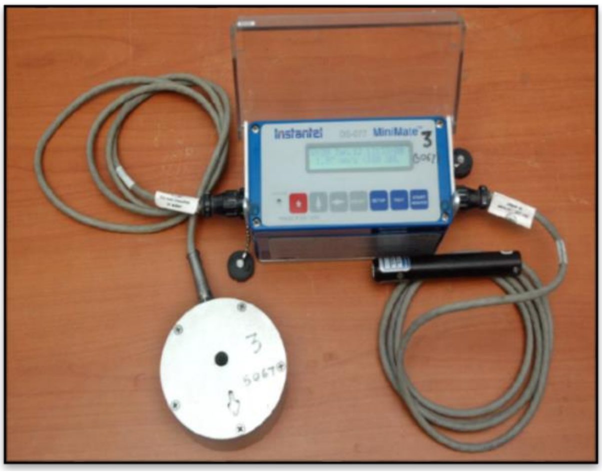

Fig. 1. Three component seismograph DS-077 from M/s Instantel Inc., Canada.

The instrument was self-triggering type digital engineering seismographs having facilities to record the three components of ground vibration (127 mm/s) as well as the air-blast overpressure (106dB to 142 dB) with frequency (2 to 250 Hz). The minimum seismic and acoustic trigger levels were 0.254 mm/s and 106 dB. However, to avoid false triggers, the trigger level was set at 0.5 mm/s. The vibration was recorded when any of the three components exceeded the trigger level.

The velocity records were available for all the three components, viz. horizontal transverse (V_T), vertical transverse (V_V) and longitudinal (V_L). For the purpose of this study, the resultant PPV was calculated using square root of sum of squares of the three components. The data consisted of records at seven different locations for around 100 trial blasts at the site. Filtering out the not-triggered data, a dataset consisting of 237 records was obtained and this formed the database of this study. The descriptive statistics of the data are presented in Table 1.

Table 1. Descriptive statistics for the total dataset (237 nos.).

Variable	Mean	Median	Standard Deviation	Maximum	Minimum	Coefficient of Variation
Distance (m)	277.08	298.40	115.79	556.20	27.80	0.42
Charge Weight (kg)	5.96	5.56	1.74	8.34	2.39	0.29
PPV (mm/s)	2.77	1.65	3.61	26.75	0.58	1.30

It is noted from Table 1 that the distances ranged from 27.8 m to 556 m and the charge weight had a maximum value of 8.34 kg & minimum value of 2.39 kg. The other value of charge weight was 5.56 kg and the blasts were carried out for these three values of charge weight only. Figure 2 describes the histograms of the dataset for distances and the charge weight. Figure 2(a) represents the histogram for the distances and it appears that Normal distribution could be suitable for the distances. However, it is observed from Fig. 2(b) that most of the blasts were for charge weight of 5.56 kg, less than 50% of that number was carried out for 8.34 kg, and very few were for 2.39 kg. Thus there are three peaks in the histogram with zero values in between.

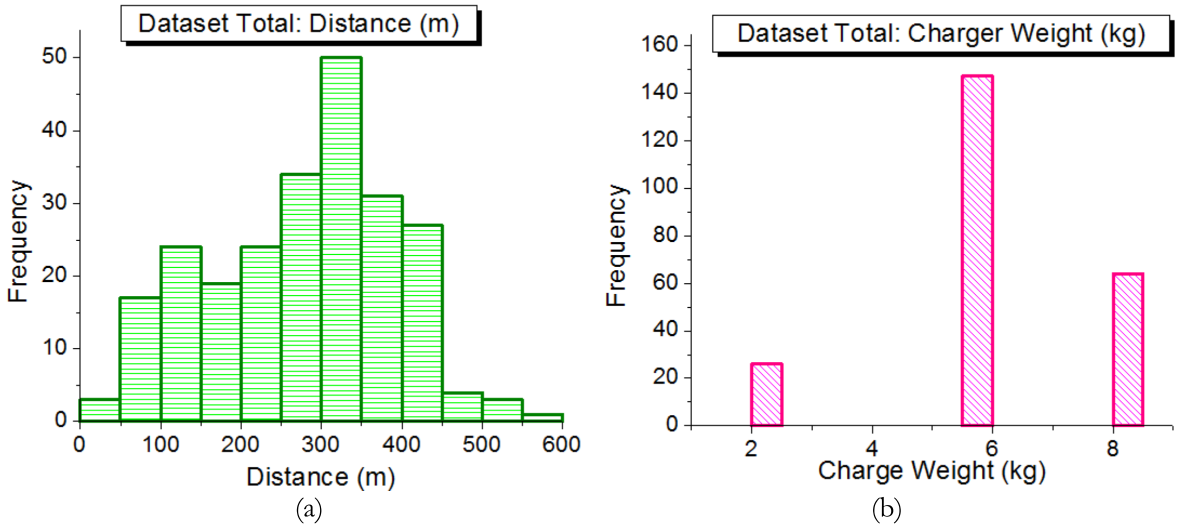

Fig. 2. Histogram for total dataset: (a) Distance; (b) Charge weight.

2.3. Methodology

It had been observed in literature that for developing the attenuation relationship for underground blasts, the parameter estimation was being carried out for the total dataset available. Then, the performance of the estimated parameters was being evaluated from the same data as was used for parameter estimation. This can be a shortcoming of the procedure normally adopted for the parameter estimation of the empirical attenuation relationship for underground blasts. Generally in data-driven approaches, model development is carried using a part (70% to 80%) of the data and evaluation of developed model is performed with remaining part of the data. Thus, in this case too, a better approach would be to use part of the data for parameter estimation and evaluate the performance of the estimated parameters from remainder of the data.

Hence for this study, two representative subsets, each consisting of 100 data were selected randomly from the total dataset (237 data) which would be referred as Set A and Set B subsequently. For subset A and subset B, the remainder of the data is defined as the conjugate sets: subset A' and subset B' respectively. The histograms obtained for the distances in the subsets A, A', B, and B' are presented in Fig. 3. It is evident that though there are incidental variations, the histograms have similar shape for all the cases as well as the total data in Fig. 2(a) indicating the representative nature of the subsets. This similarity was observed for the charge weight also (Fig. 4).

In the present study, the subsets A and B are used for parameter estimation. The performance of the estimated parameters are evaluated by both the subsets A & A', and B & B'. The comparison of performance evaluation by A & A' and B and B' would bring out the differences, if any, due to using a different set of data for evaluation of performance. This exercise will help to identify whether evaluation of performance of estimated parameters from the same dataset as used for parameter estimation results in shortcoming of the selected expression in case of underground blasts.

Three types of expressions were explored to represent the relationship between the scaled distance and the PPV to choose the best fit expression. They were the Weibull model (Eq. 3), the Power expression (Eq. 2), and the Reciprocal expression (Eq. 4).

$$PPV = a - b\, e^{-cX^d} \tag{3}$$

$$PPV = \frac{1}{aX+b} \tag{4}$$

where, *a, b, c, d*: empirical constants and X is defined by Eq. (1).

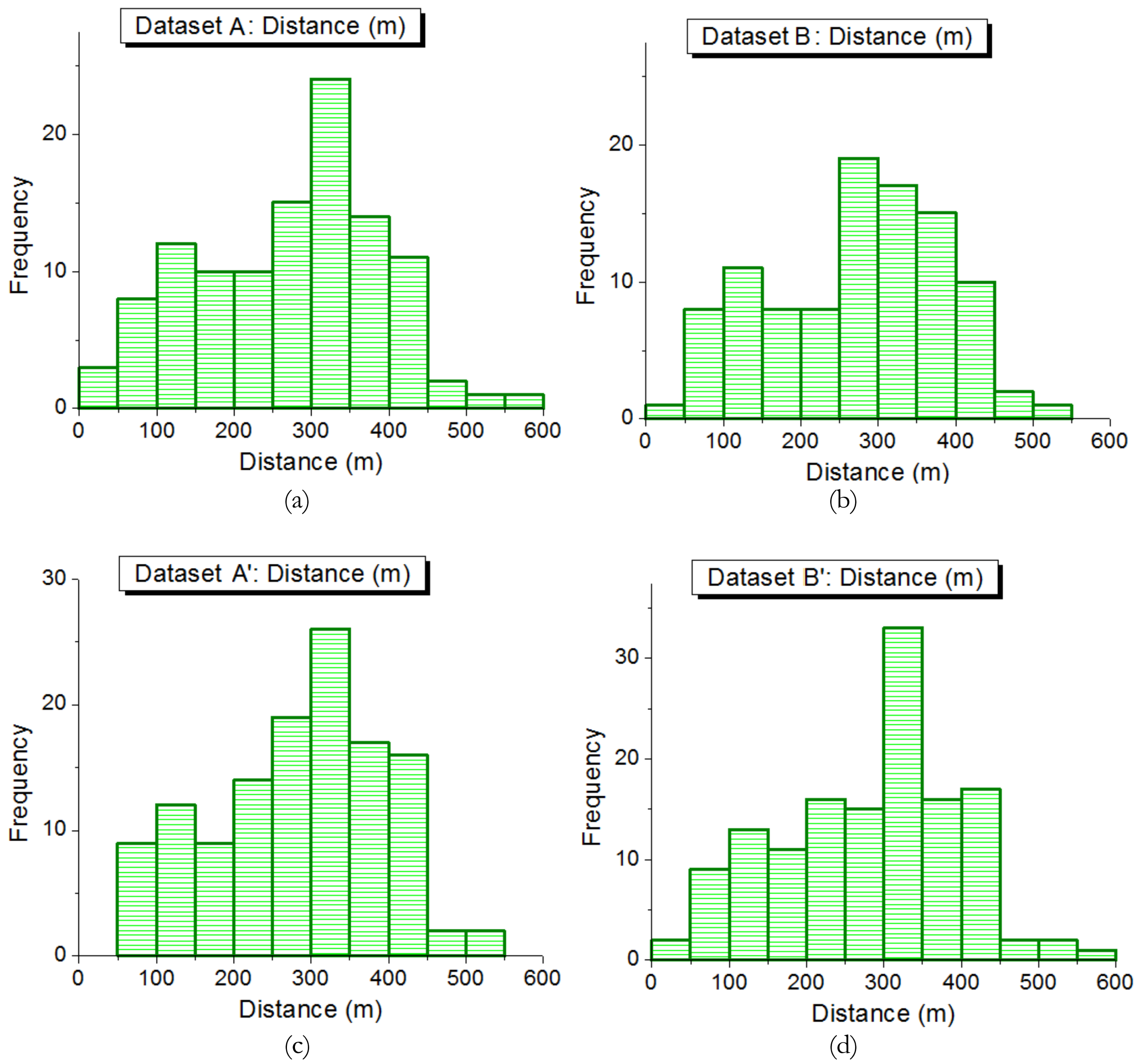

Fig. 3. Histogram for distances: (a) Subset A; (b) Subset B; (c) Subset A'; (d) Subset B'.

Parameter estimation was performed from the subsets A and B with the exponent '*n*' in Eq. (1) varied between 0.4 and 0.75 (n = 0.4, 0.5, 0.6, 0.667 and 0.75) for each of the expressions. The best value for exponent and the best suited among the three expressions were identified for each of the subsets A, A', B, and B'.

The suitability of the expressions used and the parameters estimated were evaluated quantitatively by Correlation Coefficient (R), Mean Square Error (MSE), and Akaike Information Criterion (AIC) and qualitatively with scatter plot and variable plot for all individual data subsets. The value of R signifies the linear association between the two variables and a value closest to unity is better. The MSE indicates the overall accuracy of the estimates and lower value is better. The metric AIC indicates the overall accuracy of the estimate as well the parsimony of the expression and lower value is better. This is especially useful when comparing relationships with different number of empirical constants. In the scatter plot, the relationship yielding the lineation of points closest along the 1:1 line would be the better one.

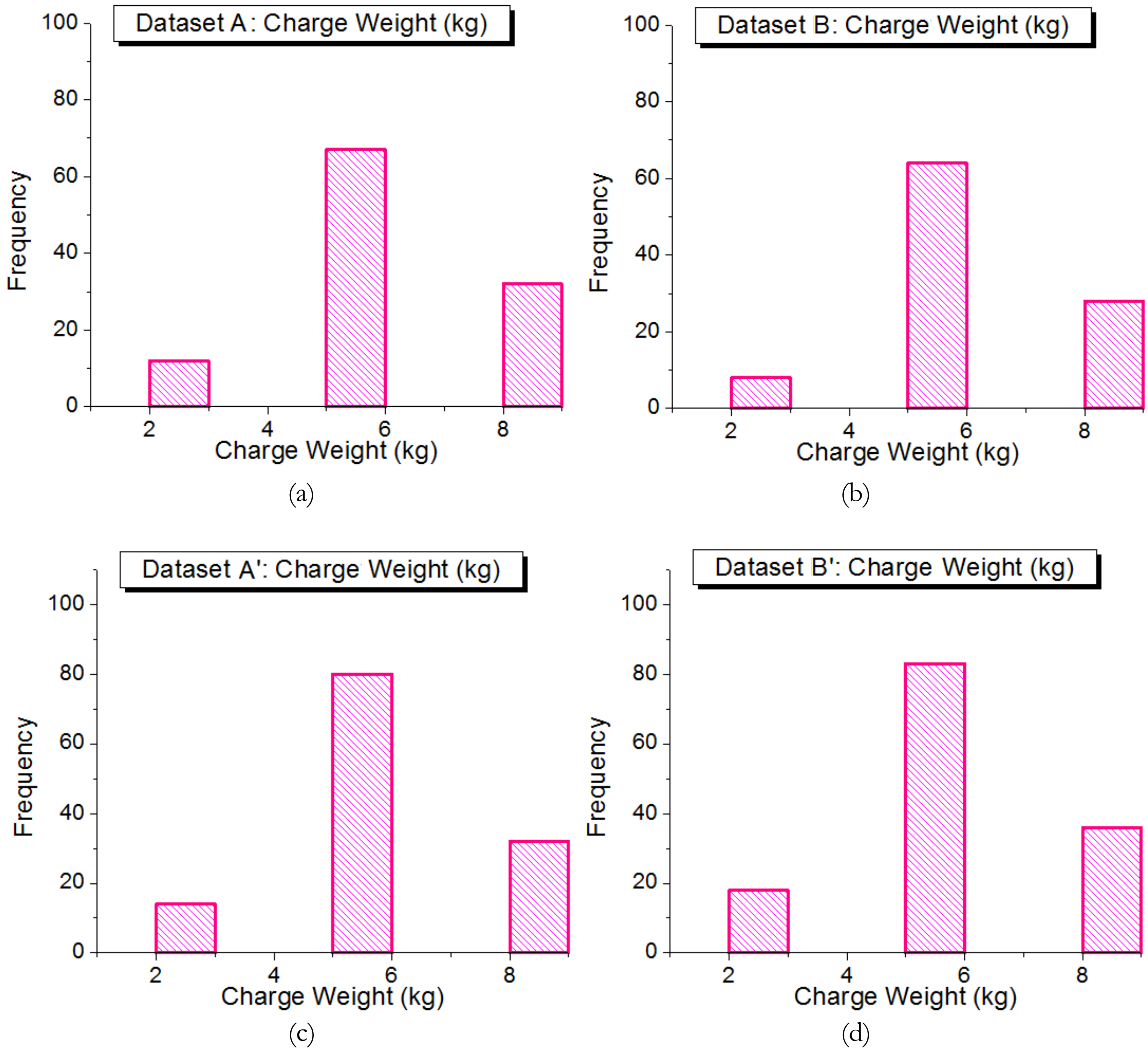

Fig. 4. Histogram for charge weights: (a) Subset A; (b) Subset B; (c) Subset A'; (d) Subset B'.

3. Results and Discussions

3.1. Performance Evaluation for Subset A and Subset A'

The results are presented in this section first for the case where parameter estimation is done with dataset A and evaluation of the developed relationship is performed both with data subset A and the conjugate subset A'. The quantitative performance measures such as correlation coefficient (R), the mean squared error (MSE) and the Akaike information criteria (AIC) for evaluation with subset A is presented in Table 2 and that for the subset A' in Table 3.

From the performance metrics from Table 2, the optimal exponent as evaluated for Weibull model is 2/3, for reciprocal expression is 2/3, for power expression is 0.6. This indicates that different exponent values should be explored for the best suited site specific attenuation relation. When evaluating the performance measures with data subset A, the best expression is the Weibull model as in this case, the parsimony can be disregarded for model development with 100 data. The performance plots for the best expression are depicted in Fig. 5.

Table 2. Performance evaluation with data subset A.

Exponent in Eq. (1) ⇨		0.4	0.5	0.6	2/3	0.75
	R	0.9510	0.9527	0.9536	0.9539	0.9537
Weibull	MSE (mm/sec)	1.2824	1.2412	1.2166	1.2102	1.2141
	AIC	7.5025	7.5678	7.6079	7.6184	7.6120
	R	0.9442	0.9451	0.9456	0.9457	0.9454
Reciprocal	MSE (mm/sec)	1.4609	1.4354	1.4229	1.4212	1.4376
	AIC	3.2419	3.2771	3.2946	3.2970	3.2740
	R	0.9451	0.9459	0.9461	0.9460	0.9454
Power	MSE (mm/sec)	1.4432	1.4289	1.4302	1.4402	1.4634
	AIC	3.2663	3.2862	3.2844	3.2704	3.2385

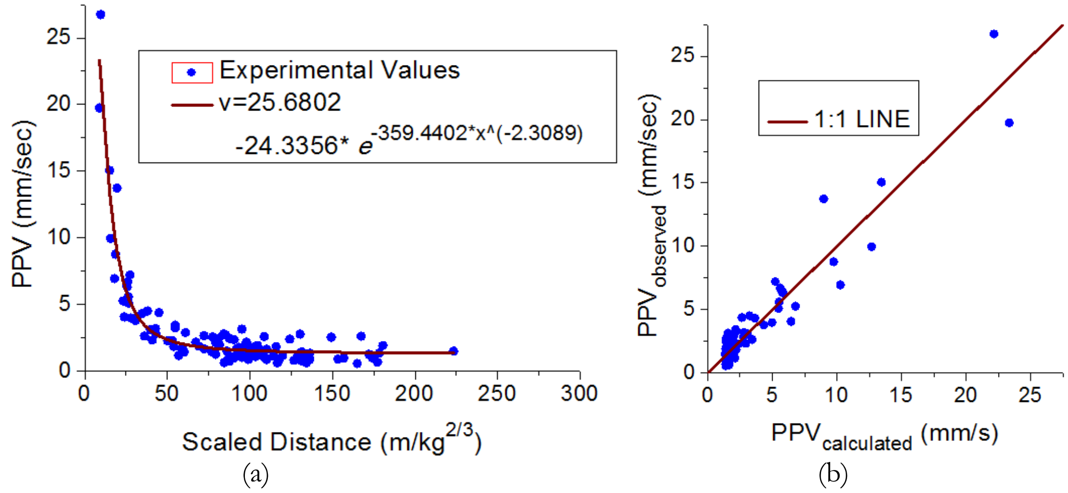

Fig. 5. Performance of best expression (Weibull Model) for data subset A: (a) Variable plot; (b) Scatter plot.

Table 3. Performance evaluation with data subset A'.

Exponent in Eq. (1) ⇨		0.4	0.5	0.6	2/3	0.75
	R	0.7273	0.7371	0.7460	0.7515	0.7577[@]
Weibull	MSE (mm/sec)	6.3742	6.1818	5.9960	5.8784	5.7391[@]
	AIC	4.2955	4.3568	4.4178	4.4574	4.5054[@]
	R	0.7308	0.7384	0.7451	0.7491	0.7538
Reciprocal	MSE (mm/sec)	6.2931	6.1282	6.0405	5.8897	5.7299
	AIC	0.3211	0.3742	0.4030	0.4536	0.5086
	R	0.7323	0.7402[$]	0.7471	0.7514[#]	0.7562
Power	MSE (mm/sec)	6.2074	6.0400[$]	5.8861	5.7912[#]	5.6809
	AIC	0.3485	0.4032[$]	0.4548	0.4873[#]	0.5258

[@] Best Expression from Proposed Approach; [$] Expression in Industrial Practice; [#] IS Code Expression

From the performance metrics from Table 3, the optimal exponent as evaluated for Weibull model is 0.75, for reciprocal expression is 2/3, for power expression is 0.75. This confirms that different exponent values should be explored for the best suited site specific attenuation relation. When evaluating the performance measures with data subset A', the best expression is the again Weibull model; as explained earlier, the parsimony can be disregarded. The best performing expression performance plots are presented

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in Fig. 6. The performance scatter for the fresh data subset (Fig. 6(b)) is markedly more than when evaluated with data subset A (Fig. 5(b)).

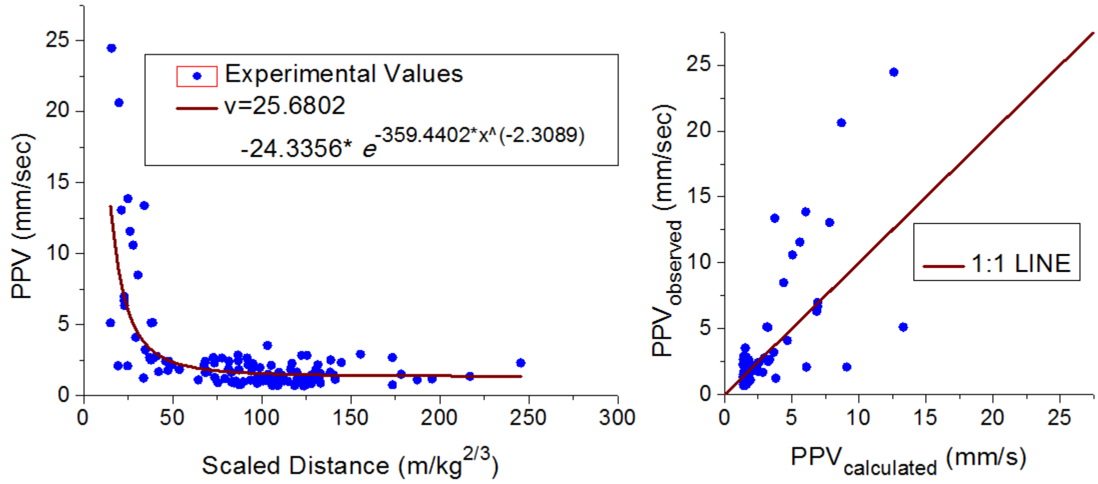


Fig. 6. Performance of best expression (Weibull Model) for data subset A': (a) Variable plot; (b) Scatter plot.

On comparison of the Table 2 and Table 3, the performance of the testing set A' is relatively poor. For example, the best model performance (Weibull model) in subset A has correlation of 0.9539 whereas for the subset A' it falls to 0.7577. Similarly the MSE for the best model (Weibull model) in subset A of 1.2102 mm/sec increases to 5.7391 mm/sec for subset A'. This clearly shows that the evaluation of the performance of the developed expressions with a fresh testing data set would definitely change the evaluation. It is noted that in this case, a different expression from the popularly adopted Power expression, namely, the Weibull model, emerges as the best suited expression for the attenuation relationship. Further, the best suited exponent as evaluated from subset A' is 0.75, which is also different from the popularly adopted 0.5 in literature for site specific attenuation relationships or the 2/3 suggested by IS code [20]. Hence, it is advocated that for development of the site specific expressions for the vibration attenuation relationship for underground blasts, different exponents and various expressions should be explored and their performance evaluation should be done with fresh testing data set (which has not been used in estimation of model parameters) to identify the best suited expression for the site under consideration.

3.2. Performance Evaluation for Subset B and Subset B'

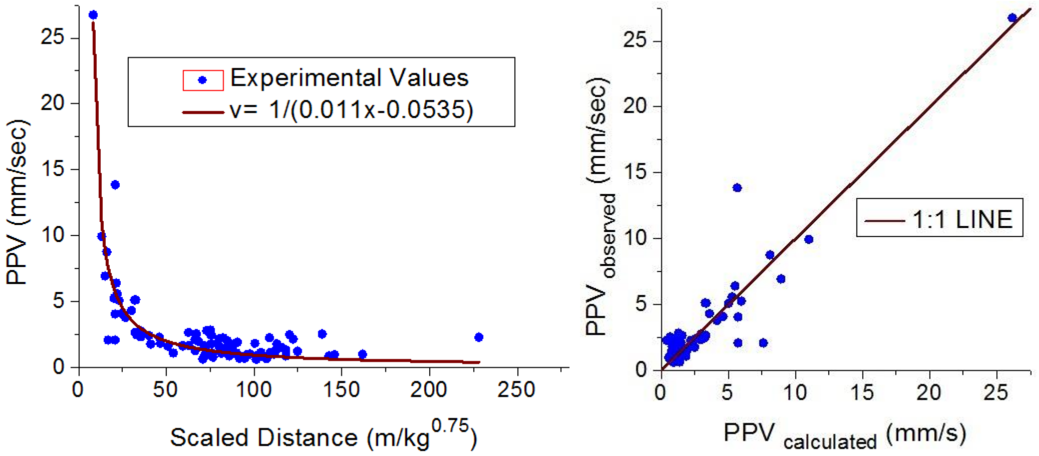
The quantitative performance measures such as correlation coefficient (R), the mean squared error (MSE) and the Akaike information criteria (AIC) for evaluation with subset B is presented in Table 4 and that for the subset B' in Table 5.

From the performance metrics from Table 4, the optimal exponent as evaluated for Weibull model is 0.75, for reciprocal expression is 0.75, for power expression is 0.6. This reconfirms that different exponent values should be explored for the best suited site specific attenuation relation. When evaluating the performance measures with data subset B, the best expression is the Reciprocal expression from correlation coefficient and Weibull model from MSE consideration. Thus either may be selected to represent the attenuation relationship. Here, on the basis of correlation coefficient, Reciprocal expression is selected as the best. The performance plots for the best performing expression is depicted in variable and scatter plots in Fig. 7.

From the performance metrics from Table 5, the optimal exponent as evaluated for Weibull model is 0.75, for reciprocal expression is 2/3, for power expression is 0.75. These are incidentally same as those identified for subset B. This re-confirms that different exponent values should be explored for the best suited site specific attenuation relation. When evaluating the performance measures with data subset B', the best expression is the well accepted Power expression (performance plots in Fig. 8), which is different from the Reciprocal expressions identified with the subset B.

Table 4. Performance evaluation with data subset B.

Exponent in Eq. (1) ⇨		0.4	0.5	0.6	2/3	0.75
	R	0.9047	0.9077	0.9101	0.9112	0.9124
Weibull	MSE (mm/sec)	1.8257	1.7710	1.7278	1.7065	1.6851
	AIC	6.7961	6.8569	6.9063	6.9311	6.9564
	R	0.9089	0.9115	0.9136	0.9091	0.9156
Reciprocal	MSE (mm/sec)	1.7996	1.7607	1.7335	1.8662	1.7168
	AIC	2.8249	2.8686	2.8997	2.7522	2.9191
	R	0.8902	0.8917	0.8925	0.8920	0.8920
Power	MSE (mm/sec)	2.1881	2.1761	2.1797	2.1913	2.2170
	AIC	2.4339	2.4449	2.4416	2.4310	2.4077



(a) (b)

Fig. 7. Performance of best expression (reciprocal expression) for data subset B: (a) Variable plot; (b) Scatter plot.

Table 5. Performance evaluation with data subset B'.

Exponent in Eq. (1) ⇨		0.4	0.5	0.6	2/3	0.75
	R	0.7487	0.7561	0.7628	0.7670	0.7712
Weibull	MSE (mm/sec)	9.3655	9.1246	8.8982	8.7559	8.6184
	AIC	3.5259	3.5781	3.6283	3.6605	3.6922
	R	0.7524	0.7589	0.7647	0.7923	0.7735
Reciprocal	MSE (mm/sec)	9.6757	9.5051	9.3599	8.6425	9.1490
	AIC	-0.5392	-0.5037	-0.4729	-0.3134	-0.4273
	R	0.8105	0.8180$	0.8250	0.8293#	0.8345@
Power	MSE (mm/sec)	7.9754	7.7555$	7.5484	7.4190#	7.2654@
	AIC	-0.1527	-0.0968$	-0.0427	-0.0081#	0.0338@

@ Best Expression from Proposed Approach; $ Expression in Industrial Practice; # IS Code Expression.

There is drastic change in the performance metrics between the data subset B and conjugate subset B', along with a wider scatter in dataset B', and this is similar to the behaviour observed in case of data subset A and conjugate subset A'. The lowest performance when evaluated with the subset with which parameters were estimated converted to the best performance when evaluated with a fresh data subset. Based on these results, it is strongly suggested that for development of the site specific expressions for the vibration attenuation relationship for underground blasts, different exponents and various expressions should be explored and their performance evaluation should be done with fresh testing data set (which has not been used in estimation of model parameters) to identify the best suited expression for the site under consideration.

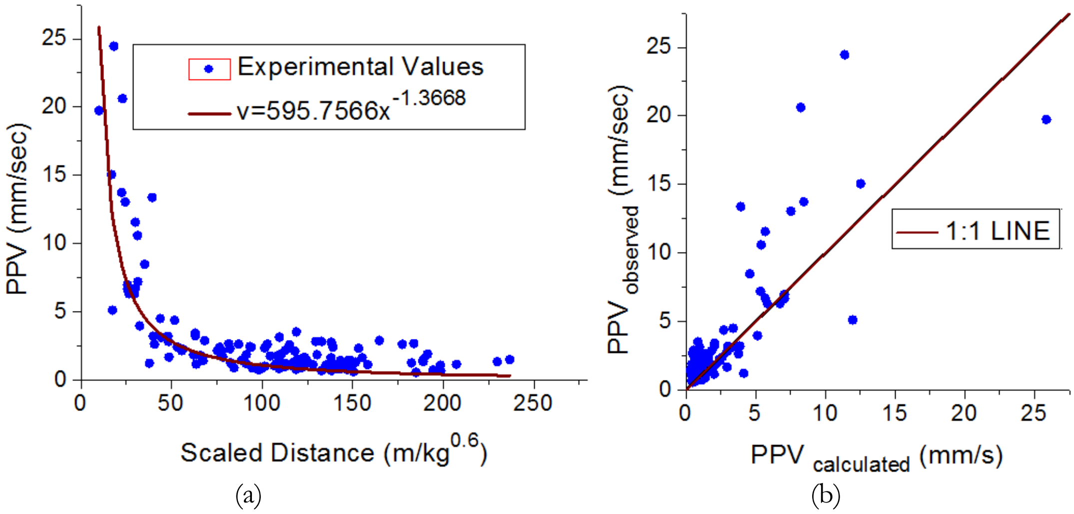


Fig. 8. Performance of best expression (power expression) for data subset B': (a) Variable plot; (b) Scatter plot.

3.3. Discussion

The industrial approach fixes the expression form and the exponent and suggests estimation of the empirical constants *a* and *b* from the available data. The performance evaluation is just for record. IS code fixes the form of expression and the exponent, as well as the empirical constants. The proposed approach suggests exploration of different expressions, various exponents and actual performance evaluation from the site data to arrive at the attenuation relationship for underground blasts. Evidently, the proposed approach is computation intensive when compared to the industrial practice or the IS code approach, which may be considered as a disadvantage. However, the estimated expression is derived by careful examination of the various performance indices resulting in selection of the best performing model. It has been demonstrated with two sample datasets that the proposed approach would result in superior performance when compared to the industrial practice or the IS approach. This would be the advantage of the proposed method.

4. Summary and Conclusions

In this article, the following have been investigated for development of site specific vibration attenuation relationship for underground blasts:

i. Whether performance evaluation of the developed expression with the same dataset as was used for parameter estimation and with a different testing dataset would be different;
ii. Whether exponents other than the IS code specified [20] 2/3 or popularly adopted value for site specific relationship of 0.5 in Eq. (1) could be better;
iii. Whether expressions other than the universally popular Power expression could be better;

For this purpose, trial blast data from a site was taken as a case study. Exponents ranging from 0.4 to 0.75 were examined in conjunction with two expressions, namely, Weibull model and the Reciprocal expression, being explored along with the popular Power expression. The performance evaluation was done with the data subset used for the parameter estimation (A) as well as fresh data subset (A'). This exercise was repeated for another representative subset B and conjugate subset B' in order to eliminate any incidental findings with a single dataset (say, A). From the study, the following conclusions are drawn:

i. Evaluation of performance with the same dataset from which the model parameter estimation was done, yields artificially enhanced performance and may result in selection of non-optimal model. This is expected and this is the very reason for the suggested practice of empirical parameter estimation from a subset of the available data and performance estimation from the conjugate subset.

ii. Exponents other than the IS code specified [20] 2/3 or popularly adopted value of 0.5 for site specific relationship in Eq. (1) have been found to be better in the case study. For both the testing subsets A' and B', exponent of 0.75 was found to be optimal. Hence, various exponents should be explored for arriving at the best for the particular site.

iii. Other expressions may be better suited than Power expression as Weibull model was optimal for data subset A'. Thus, for each site different expressions should be examined to identify the best suited expression.

It is hereby recommended that for true performance evaluation, suitability of the estimated parameters for the expression should always be evaluated with a fresh dataset that had not been a part of the parameter estimation. Different expressions (for example, Reciprocal expression, Power expression, Weibull model) should be examined along with the various exponents for the scaled distance (Eq. (1)) to arrive at the best possible representation of the vibration attenuation relationship for underground blasts. The difference in performance of the different expressions and also when performance is evaluated with the parameter estimation set & the conjugate (fresh) set observed in this study are low. This could be due to the large data set (100 nos.) used in parameter estimation. When dealing with less number of data, the differences could be larger and the benefits of adoption of the recommended methodology would be more apparent. Future work may be directed towards exploring other suitable expressions for the relationship, and for examining the influence of the number of data on the developed relationships.

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