Estimation of Vibration Parameter for Blast Based on Shear Strength

Ranjan Kumar[1], Pravin Prakash Yerunkar[2], and Kapilesh Bhargava[3]
[1]*Civil engineering Division, Bhabha Atomic Research Centre, Trombay, Mumbai, India*
[2]*Discipline of Engineering Sciences, Homi Bhabha National Institute, Anushaktinagar, Mumbai, India*
[3]*Nuclear Recycle Board, Bhabha Atomic Research Centre, Trombay, Mumbai, India*
E-mail: ranjancv42@gmail.com

ABSTRACT: The topic of blast loads on structures has received considerable attention of researchers and various site specific empirical models for blast induced vibration parameters such as Peak Particle Velocity (PPV) already exist. However, these empirical models do not consider the variation in soil property namely shear strength. In this paper, a total of 166 blast data from various soil sites have been collected and used to propose a generalized empirical model to estimate PPV in terms of shear strength. The presented empirical model has been compared with the models of other researchers. It has been found that the presented model, having maximum coefficient of correlation and minimum standard error, can be directly used in calculation of PPV. In the absence of field blast vibration data, the present model will be very useful to evaluate blast vibration parameter by using only basic soil property specified in terms of shear strength. The present model has also been validated for various degrees of saturation of soil. It is concluded that the present model predicts slightly higher values (i.e. critical values for design purposes) for partially saturated alluvium and sand, and predicts fairly for partly saturated tuff, wet tuff, saturated alluvial and loess.

KEYWORDS: Disaster engineering, Geotechnical engineering, Safety & hazards.

1. INTRODUCTION

Ground shock propagation in earth media is a complex function of the dynamic constitutive properties of the soil, the explosive products and geometry of the explosion. No single soil index or combination of indices can adequately describe this process in a simple way for all the cases. Water saturation can have a profound influence on ground shock propagation in cohesive soils and relatively low density sand, whereas, granular soils with high relative density are not strongly influenced by water saturation (Drake and Little, 1983). In short, soil conditions such as soil type, density and degree of saturation can significantly affect the manner in which ground shock propagates through the ground (Leong et al., 2007). The shear strength parameter can effectively describe the condition of the soil and the same can be adequately used in estimating the propagation of ground vibration.

Peak particle velocity (PPV) has been commonly adopted as a parameter to characterize ground vibration since 1950s. Most conventional empirical models relate PPV to scaled-distance (*SD*) which depends upon the charge weight per delay and the distance between detonation and monitoring point. The PPV and *SD* are plotted in a logarithm-logarithm space and they are often fitted by a linear model despite the fact that the data could be quite scattered. The first significant PPV predictor equation was proposed by the United States Bureau of Mines (1962). There are also modified predictors from other researchers or institutions such as Ambraseys and Hendron (1968), Langefors and Kihlstrom (1978), Ghosh and Daemen (1983), Roy (1991), Singh et al. (2002) etc. A viscoelastic cap model was developed for simulation of soil behavior under blast loading to take care of high strain effect by An et al. (2011). Artificial Neural Network (ANN) was used to estimate the specific charge in various conditions of tunnel blasting by Alipour et al. (2012). Soil structure interaction and the effect of saturated soil compressibility (inverse of Bulk Modulus) on damage of a cast iron subway tunnel under internal blast loading was studied by Liu (2012). Kumar et al. (2014) provided empirical relation of PPV in terms of Young's modulus, unit weight and degree of saturation of soil. However, the PPV predictor established by USBM is still the most widely used equation in the literature which establishes that the blast should be scaled to the equivalent distances or scaled distance.

The present paper aims to investigate the relationship between PPV and scaled distance for underground blast in soil sites. An empirical model is proposed for PPV by considering a wide range of published experimental blasts at different soil sites. The model includes the contribution of engineering property of soil in terms of its shear strength. The development of soil model is proposed in this paper as follows: (1) experimental data of various researchers for blast sites have been collected, where description of the site in terms of Bulk density, Unit weight of soil, degree of saturation, voids ratio or porosity has been mentioned; any missing parameter is assigned based on description in the literature, (2) shear strength is then assigned to various sites considered, and (3) The empirical soil model has been developed.

2. PROPOSED MODEL FOR BLAST VIBRATION PREDICTION

The blast vibration prediction in terms of PPV for a site can be written as Eq. (1) (Dowding, 1985).

$$v = kD^{-\beta} \tag{1}$$

Cube root scaling is considered in the present study of ground vibration. Generally, blast experiments are conducted to determine site constants k and β. In the absence of field blast data, these constants are determined by various site specific empirical equations developed on the basis of blast data. The summary of 10 different empirical models of various researchers is given in Table 1. Unlike Kumar et al. (2014), these models are able to predict PPV for their corresponding sites but they fail to provide fair prediction for other sites. No single PPV model has considered shear strength of soil in the prediction model. Shear strength depends upon a broad range of soil properties i.e. angle of internal friction, cohesion, unit weight, degree of saturation etc.

Table 1 Summary of various researchers' models to estimate PPV

S/No	Researcher	Empirical model
1	BIS 6922 (1973)	$v = 0.88(W^{2/3}/R)^{1.25}$
2	William and Robert (1975) Soil type: Alluvium	$v=4.59(R/W^{1/3})^{-3.27}$
3	William and Robert (1975) Soil type: Dry Tuff	$v=5.587(R/W^{1/3})^{-1.98}$
4	William and Robert (1975) Soil type: Wet Tuff	$v=2(R/W^{1/3})^{-1.56}$
5	Charlie et al. (1992) Soil type: Saturated Alluvial Soil	$v=8.75(R/W^{1/3})^{-2.06}$

6	Gandhi et al. (1999) Soil type: Ash Deposits	$v=14.054(R/W^{1/3})^{-2.8286}$
7	Negmatullaev et al. (1999) Soil type: Loess	$v=74.13(R/W^{1/3})^{-1.46}$
8	Lu (2005) Soil type: Stiff Clay	$v=160(R/W^{1/3})^{-2.5}$
9	Leong et al. (2007) Soil type: Partially Saturated Soil	$v=36.1(R/W^{1/3})^{-2.89}$
10	Kumar et al. (2014)	$v=(E/\gamma)^{0.229}(R/W^{1/3})^{-(1.6985-0.175\times S)}$

v, *W* and *R* are PPV, charged weight and blast distance respectively

3. DEVELOPMENT OF EMPIRICAL MODEL FOR PPV

A total of 166 published field blast data of 6 different researchers in terms of PPV and scaled distance were collected. Normalized values of PPV are plotted against scaled distance for the field blast data as shown in Figure 1.

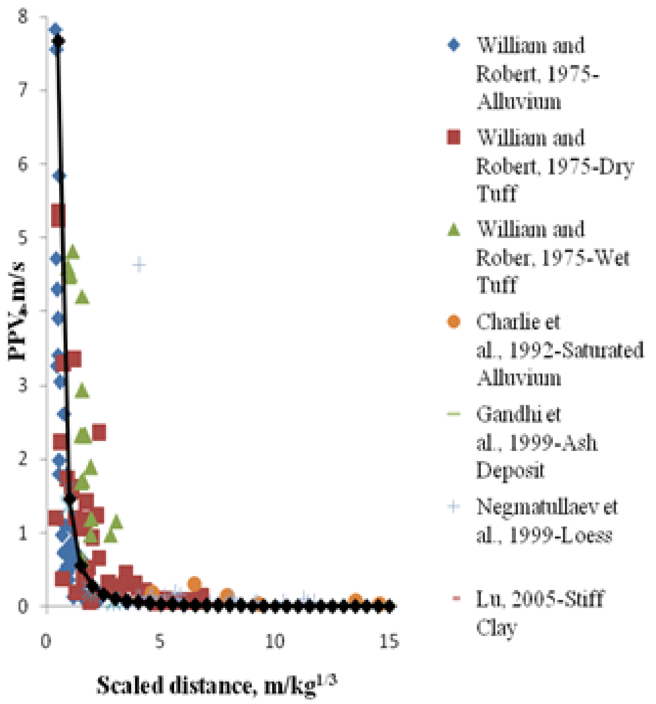

Figure 1 Plot of normalized PPV (m/s) as a function of Scaled distance (m/Kg$^{1/3}$) for experimental data

Most of the researchers while obtaining the blast data, have also described the geological conditions and soil properties existing at the site. Most of the data for determining the shear strength were available; however, certain data which were not determined or obtained during site investigation have been suitably assigned based on description of the site in the literature. Shear strength assigned to different soil types in the above studies are given in Table 2.

Table 2 Calculation of Shear Strength with other available soil parameters for experimental data

Researchers	Soil	c' kN/m^2	φ', degree	γ', kN/m^3	Shear Strength, kN/m^2
William and Robert, 1975	Alluvium	0	41.5	17.46	3292.584
William and Robert, 1975	Dry Tuff	0	42.5	17.46	3049.283
William and Robert, 1975	Wet Tuff	0	42.5	17.46	8372.636
Charlie et al., 1992	Saturated Alluvial Soil	0	28.5	18.4	41.157
Gandhi et al., 1999	Ash Deposit	7.5	20	10.69	17.452
Negmatullaev et al., 1999	Loess	0	28.5	26.19	57.161
Lu, 2005	Stiff Clay	7	34	18.64	546.375
Leong et al., 2007	Partially Saturated Soil	0	37.5	16.19	39.243

The soil properties, namely, cohesion and angle of friction were given by few researchers along with their data. Once Effective stress is calculated, Shear Strength can be determined by Eq. (2).

$$\tau = C + \sigma' \tan \varphi \qquad (2)$$

Depth of explosive and depth of instrument for measurement were different for same site. Shear strengths at both the depths have been estimated. Average of shear strength at these two depths has been considered as input shear strength value. When depth of explosive and depth of instrument were same, the estimated shear strength was same. Cohesion and angle of friction of two sites were given (Lu, 2005 and Gandhi et al., 1999). Cohesion and angle of friction of other sites of four researchers (William and Robert, 1975; Charlie et al., 1992; Negmatullaev et al., 1999; Leong et al., 2007) are assigned based on the description and other properties such as type of soil, degree of saturation, grain size etc. provided by the researchers. The soil properties are presented in Table 2. Presence of water table is also considered.

The shear strength assigned to different site under investigation were fitted into the linear equations obtained by using CurveExpert 1.37 software developed by Daniel (2001). It was found that assigned shear strength parameter was fitting into the linear equation as well as attenuation factor. These scales were first converted into logarithmic scale and then plotted in CurveExpert 1.37. A linear relationship was established between them. The summary of the log linear equations and the equations with the shear strength are given in Table 3. It is observed from Table 3 that the power to the shear strength and the scaled distance were not uniform. Consequently, the weighted mean of their powers was calculated and the final value of this power was obtained.

Table 3 Summary of log linear equation and equation with shear strength properties

Researcher	Shear Strength	data	Relationship; $v=k*D^b$	
			Log linear equation	Equation with properties
William and Robert, 1975	3293	28	$1.013*D^{-2.03}$	$\tau^{-0.00159}*D^{-7.1406/\log\tau}$
William and Robert, 1975	3049	49	$1.012*D^{-1.43}$	$\tau^{0.00149}*D^{-4.9824/\log\tau}$
William and Robert, 1975	8373	14	$3.346*D^{-1.29}$	$\tau^{0.13371}*D^{-5.0605/\log\tau}$
Charlie et al., 1992	41	10	$6.905*D^{-2.0}$	$\tau^{0.51978}*D^{-3.2289/*\log\tau}$
Gandhi et al., 1999	17	14	$2.96*D^{-2.2}$	$\tau^{0.3795}*D^{-2.73204/\log\tau}$
Negmatul-laev et al., 1999	57	35	$1.065*D^{-1.36}$	$\tau^{-0.01557}*D^{-2.38965/\log\tau}$
Lu, 2005	546	9	$1.088*D^{-1.87}$	$\tau^{-0.01338}*D^{-5.1191/\log\tau}$
Leong et al., 2007	39	7	$1.214*D^{-2.64}$	$\tau^{0.05284}*D^{-4.20753\log\tau}$

Based on the experimental data shown in Figure 1, the following generalized empirical model in Eq. (3) with r^2 = 0.80 and s^2= 0.35 is proposed in the present study to evaluate PPV for soil sites. The present model prediction line is plotted in Figure 1 along with experimental data of various soil sites.

$$v = \tau^{0.082} D^{-4.49/log\tau} \quad (3)$$

4. INVESTIGATING PERFORMANCE OF THE PROPOSED MODEL

The experimental data obtained by various researchers during site investigations are plotted together in Figure 1 so as to facilitate easy validation of the proposed model. Figure 1 presents the plot of normalized PPV as a function of *SD* as obtained from Eq. (3) for the various sites. It is seen from Figure 1 that the experimental data obtained by the researchers are scattered over the plot because of the fact that it has been taken from different sources having different testing procedures and site conditions.

By estimating the correlation between the predicted and measured values in Figure 1, the performance of Eq. (3) can be investigated. Assuming that x = Predicted PPV (the independent variable) and y = Measured PPV (the dependent variable); for Eq. (3), the values of both r_{xy}^2 and s_{yx}^2 were calculated and obtained as 0.80 and 0.35 respectively. Predicted PPV and measured PPV are plotted in Figure 2. It is evident from Figure 2 that the deviations between predicted and measured values are generally less than by a factor of two and this is a considerably good agreement.

The values of r_{xy}^2 and s_{yx}^2 associated with various empirical models are given in Table 4 along with the present model for prediction of measured blast data. Plots of r_{xy}^2 and s_{yx}^2 are given in Figure 3 and Figure 4 respectively. It is clear from the Table 4, Figure 3 and Figure 4 that, the present model provides the best correlation between the predicted and actual measured values as compared to the other existing empirical models for estimation of PPV because of the highest r_{xy}^2 and lowest s_{yx}^2 associated with it.

Data outside the purview were also predicted. Data of other researcher Al-Qasimi et al. (2005) was also predicted and the value of values of r_{xy}^2 and s_{yx}^2 were found to be 0.82 and 0.36 respectively which is acceptable. Data of fully saturated clay of Leong et. al. (2007) was also predicted and found to be in good agreement.

Table 4 Estimation of r_{xy}^2 and s_{yx}^2 for various blast experiments based on empirical models

Researcher	Prediction of all experimental data	
	Coefficient of determination, r_{xy}^2	Square of standard error, s_{yx}^2
William and Robert (1975)	0.67	0.57
William and Robert (1975)	0.76	1.24
William and Robert (1975)	0.67	10.76
Charlie et al. (1992)	0.75	26.62
Gandhi et al. (1999)	0.70	268.22
Negmatullaev et al. (1999)	0.78	694.33
Lu (2005)	0.72	17.77
Leong et al. (2007)	0.72	17.77
Kumar et al. (2014)	0.78	0.36
Present Model	0.80	0.35

The collected experimental data from the literature includes various types of soils with varying degrees of saturation. The predictions of experimental data by the present model for individual experimental values are shown in Figures. 5-10.

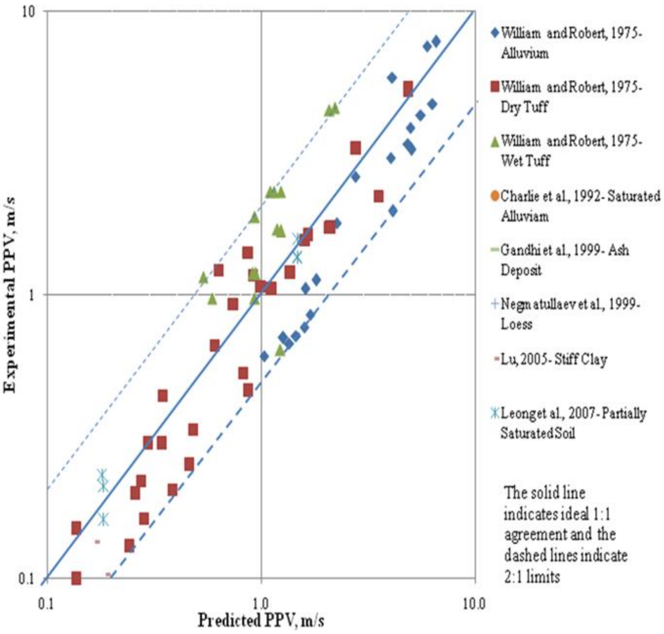

Figure 2 Comparison between experimental PPV and predicted PPV using proposed empirical model in present study

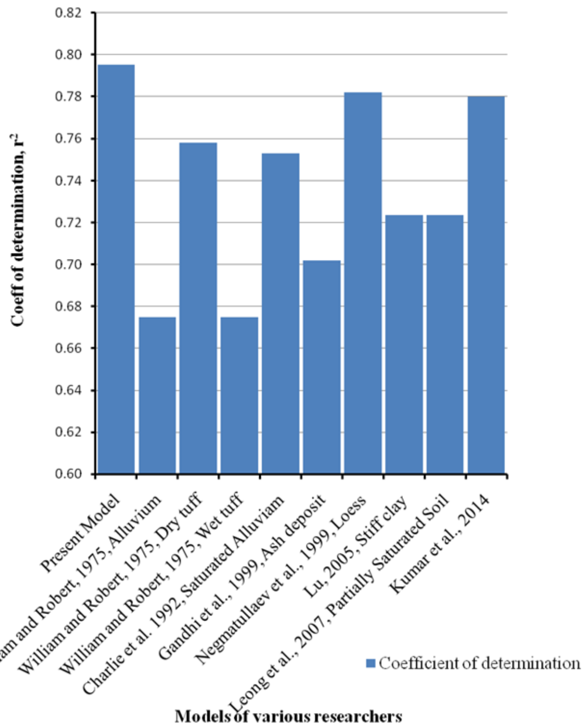

Figure 3 Comparison of Coefficient of determination (r_{xy}^2) of empirical models of various researchers

It is observed from Figures 5-10 that the predicted PPV predicts higher values (critical values for design) for partly saturated alluvium and sand, and predicts fairly for partly saturated tuff, wet tuff, saturated alluvial and loess. Degree of attenuation for alluvial soil and loess is more than that for tuff soil for the same degree of saturation. The PPV values for fully saturated tuff soil are more than those for partly saturated tuff soil. The degree of attenuation for fully saturated sand is found to be less than that for other fully saturated soils. Hence, these predictions are generally in good agreement with the experimental trends observed by various researchers for different degrees of saturation of soils.

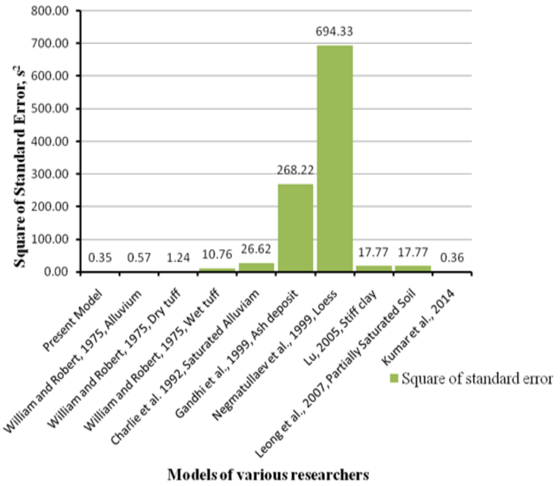

Figure 4 Comparison of square of Standard Error (s_{xy}^2) of empirical models for various researchers

It is also observed from Figures 5-10 that the present soil model predicts fairly for fully saturated soils irrespective of soil type, but it gives higher values for partially saturated soils. It may be noted that the prediction of higher values for partially saturated soils gives critical values for design.

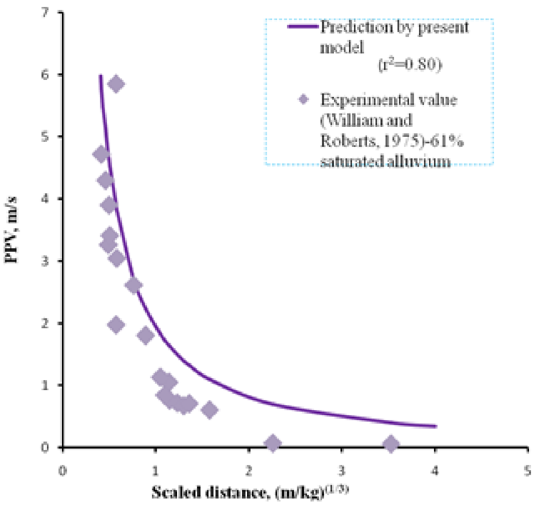

Figure 5 Prediction by present soil model for 61% saturated alluvium experimental values

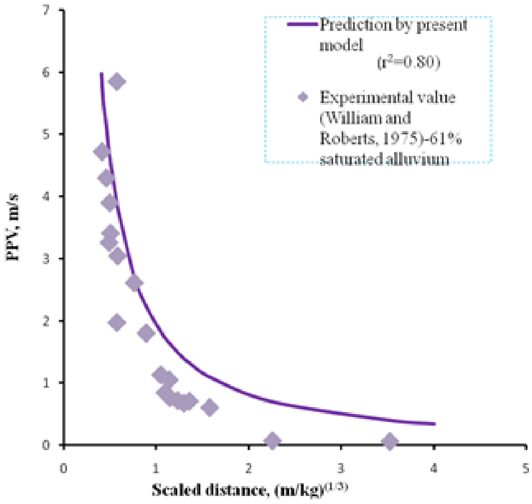

Figure 6 Prediction by present soil model for 61% saturated tuff experimental values

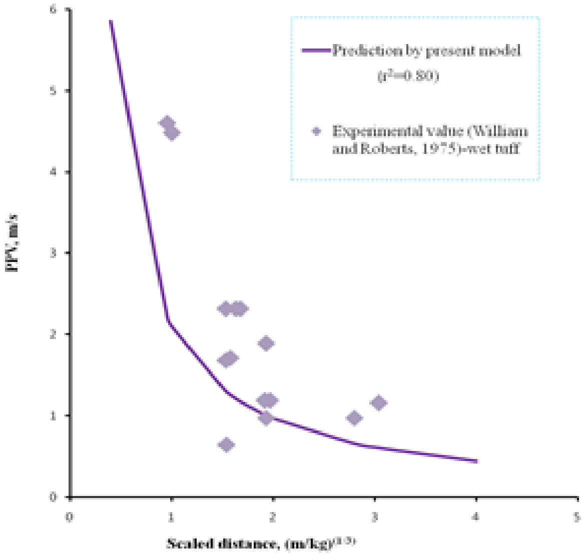

Figure 7 Prediction by present soil model for saturated tuff experimental values

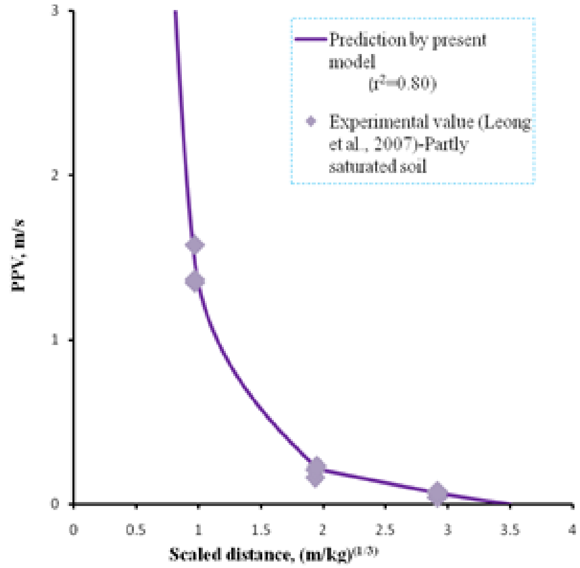

Figure 8 Prediction by present soil model for partly saturated soil experimental values

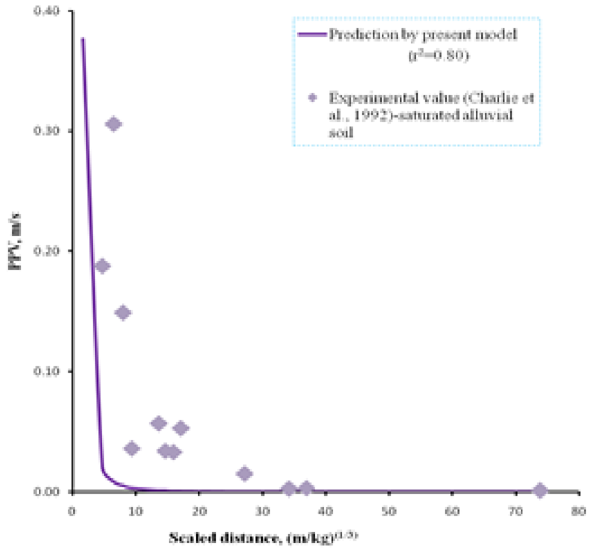

Figure 9 Prediction by present soil model for saturated alluvial soil experimental values

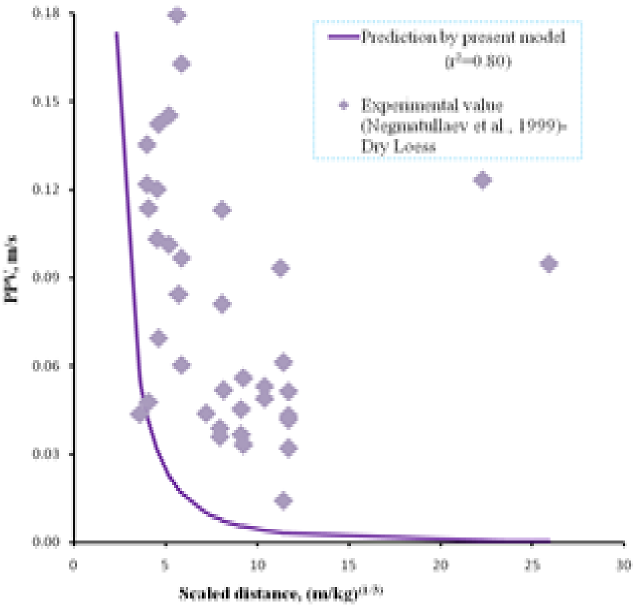

Figure 10 Prediction by present soil model for dry loess experimental values

Even though there are some differences between the measured and empirically predicted values, it can be attributed to various factors such as variation in sites, method of blasting, vibration frequency, presence of water table, discontinuities and its spacing, accuracy in measurement of vibration parameters in the present model etc. Therefore, considering the large variability associated with the blast phenomena itself and also the significant difference in the reported values of PPV among the experiments of the different researchers at various sites, the proposed empirical model predicts the trend, which are in reasonably good agreement with those of the observed experimental trend for the PPV, with maximum coefficient of correlation & minimum standard error as compared to other case specific PPV prediction models.

Different set of data (166 nos. of 6 researchers) is considered for development of present empirical model as compared to the model (120 nos. of data of 4 researchers) developed by Kumar et al. (2014). The present model is comparable with the model of Kumar et al. (2014).

5. CONCLUSIONS

Extensive experimental data (166) of various sites were collected. A simple empirical model for PPV has been proposed in terms of scaled distance and shear strength. The present study shows that the present model predicts PPV values reasonably well up to scaled distance of 7 m/kg$^{1/3}$. It has been observed that there is sudden decrease in PPV for scaled distance up to 1.5 m/kg$^{1/3}$. The effectiveness of the each model has been tested by estimating the correlation between the predicted and measured values of PPV from various sites. The Present model gives the maximum value of coefficient of determination (r^2) and lowest square of standard error (s^2). Hence, applicability of the Present model for blast related design is very good, as it considers extensive experimental data and also effective when it is compared with a large number of available empirical models. The present model has also been validated for various degrees of saturation. It is concluded that the present model predicts higher values (critical values for design) for partly saturated alluvium and sand, and predicts fairly for partly saturated tuff, wet tuff, saturated alluvial and loess.

Site specific field blast testing is very expensive tasks. Due to safety and environmental constraints, sometimes it is not possible to carry out blast tests. Hence, by using shear strength of soil existing at the site, the present PPV model can be readily used to fairly evaluate vibration parameters in the absence of field blast data.

6. LIST OF NOTATIONS

V	is the Peak Particle Velocity, m/s
D	is the Scaled Distance, m/kg$^{1/3}$ = $R/(W)^{1/3}$
k, b, β	is the Site constants
R	is the Distance from the blast point, m
h_1	is the Depth of soil
W	is the Charge per delay, kg
r_{xy}	is the Coefficient of correlation between x and y
r^2, r_{xy}^2	is the Coefficient of determination
C	is the Cohesion
C'	is the Effective Cohesion
C	is the seismic or compression or P wave velocity
σ'	is the Effective stress= $h_1 * \gamma - u$
U	is the pore pressure
Γ	is the unit weight, kN/m^3
γ'	Is the Effective unit weight, kN/m^3
φ	is the Angle of internal friction
φ'	Is the Effective angle of internal friction
s_{xy}	is the root mean square error of estimate of y on x
s^2, s_{xy}^2	is the Square of standard error
τ	is the Shear strength of soil obtained from the site in kN/m^2

7. REFERENCES

Alipour, A., Jafari, A., and Hossaini, M. F. (2012) "Application of ANNs and MVLRA for estimation of specific charge in small tunnel", International Journal of Geomechanics, ASCE, 12(2), pp1532-3641.

Al-Qasimi, E. M. A., Chalire, W. A., and Woeller, D. J. (2005) "Canadian liquefaction experiment (CANLEX): Blast induced ground motion and pore pressure experiments", Geotech. Test. J., 28(1), pp1–13.

Ambraseys, N. R, Hendron, A. J. (1968) "Dynamic behaviour of rock mass", In: Proceedings of the rock mechanics in engineering practices, London.

An, J., Tuan, C. Y., Cheeseman, B. A., and Gazonas, G. A. (2011) "Simulation of soil behavior under blast loading, International Journal of Geomechanics". ASCE, 11(4), pp323-334.

BIS 6922 (1973). Criteria for Safety and Design of Structures subject to Underground blast. BIS New Delhi.

Charlie, W. A., Jacobs, P. J., and Doehring D. O. (1992) "Blast-Induced Liquefaction of an Alluvial Sand Deposit", Geotechnical Testing Journal, GTJODJ, Vol. 15, No. 1, March 1992, pp14-23.

Daniel (2001) CurveExpert 1.37 [Computer software], Hixson, TN, D. G. Hyams.

Drake, J. L, and Little, C. D. (1983) "Ground Shock from Penetrating Conventional Weapons", The Interaction of Non-Nuclear Munitions with Structures. Symposium Proceedings Part-1, pp1-6.

Dowding, C. H. (1985) "Blast Vibration Monitoring and Control", Prentice Hall, Englewood Cliffs, NJ, 297.

Duvall, W. I., and Fogelson D. E. (1962) "Review of criteria for estimating damage to residences from blasting vibration", *US Bureau of Mines* R.I. 5968.

Gandhi, S. R., Dey, A. K., and Selvam, S. (1999) "Densification of Pond Ash by Blasting. Journal of Geotechnical and Geoenvironmental Engineering". CODEN: JGGEFK, Vol. 125, No. 10, ISSN1090-0241, pp889-899.

Ghosh, A., and Daemen, J. K., (1983) "A simple new blast vibration predictor of ground vibrations induced predictor", In: Proceedings of the 24th US symposium on rock mechanics, Texas.

Kumar R., Choudhury, D., and Bhargava, K. (2014) "Prediction of blast induced vibration parameters for soil sites", International Journal of Geomechanics, ASCE, 14(3), pp1-10.

Langefors, U., and Kihlstrom, B. (1978) "The modern technique of rock blasting", New York: John Wiley.

Leong, E. C., Anand, S., Cheong, H. K., and Lim, C. H (2007) "Re-examination of Peak Stress and Scaled Distance due to Ground Shock", International Journal of Impact Engineering 34, pp1487–1499.

Liu, H. (2012) "Soil-structure interaction and failure of cast-iron subway tunnels subjected to medium internal blast loading", Journal of Performance of Constructed Facilities, ASCE, 26(5), pp691-701.

Lu Yong (2005) "Underground blast induced ground shock and its modeling using artificial neural network", Computers and Geotechnics 32 (2005), pp164–178.

Negmatullaev, S. K. H., Todorovska M. I., and Trifunac, M. D. (1999) "Simulation of strong earthquake motion by explosions - experiments at the Lyaur testing range in Tajikistan", Soil Dynamics and Earthquake Engineering 18 (1999), pp189–207.

William, R. P., and Robert, C. B (1975) "Free-Field Ground Motion Induced by Underground Explosions", The United States Atomic Energy Commission by Sandia Corporation SAND74-0252.

Roy, P. P. (1991) "Vibration control in an opencast mine based on improved blast vibration predictors", Min Sci Technol 1991; 12, pp157*–65.*

Singh, T. N., Amit, P., Saurabh, P., and Singh, P. K. (2002) "Prediction of explosive charge for efficient mining operation", In: Proceedings of the rock engineering-problems and approaches in underground construction, Seoul, 22–24 July 2002.