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Empirical and probabilistic analysis of blast-induced ground vibrations

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ABSTRACT

An attempt has been made to include an additional blast design parameter, burden, in obtaining the vector peak particle velocity, VPPV. A large set of about 640 blast data pertaining to different rock types from ten different sites in India and Turkey has been collected from the literature. Analysis of these data has been carried out resulting in the proposal of an empirical model for peak particle velocity with due consideration to the burden along with monitoring distance and maximum charge per delay. The performance of the proposed model has been compared with existing models, and the proposed model has been found to serve the purpose of predicting VPPV with greater accuracy. Further, probabilistic analysis of VPPV has been conducted by performing Monte-Carlo (MC) simulation on proposed empirical model. Typical results corresponding to Chittorgarh limestone mines in India are presented. The input parameters namely monitoring distance and maximum charge per delay have been assumed as lognormally distributed random variables, while the burden has been assumed as discreet variable. The analysis of results of MC simulations revealed that output or the state variable, VPPV follows a lognormal distribution. It was possible to take into account the variability in the blast parameters and therefore to study its influence on VPPV.

1. Introduction

The advent of drill and blast method (DBM) in the mining and civil engineering industry, brought about a significant reformation in the rock breaking technology across the globe. Even though other technology like Rock Breakers, Tunnel Boring Machines, Road Headers, surface miners etc., have evolved with the passage of time however the explosives are still used due to its flexibility to deal with any geo-mining condition. It also brings along other benefits such as, low initial investment, cheap explosive energy, easy availability, faster rate of advancement in excavation. On the contrary, it also has many side effects such as ground vibrations, fly rock, noise etc. Amongst all the side effects of blasting, ground vibrations play a major role in affecting the stability of the existing surface structures, be they residential, commercial or structures of historical importance. It is an inevitable and integral aspect of blasting. The most intriguing portion of blasting is that approximately only 20–30% of explosive gets utilized in fragmentation and throw of rock mass, whereas the remaining 70–80% gets dissipated in the form of ground vibrations, fly rock, noise, air blasts, back break etc.[1] Literature shows that peak particle velocity (PPV) is commonly a good index of damage to structures. The most widely adopted empirical model to predict peak particle velocity is scaled distance relationship:

$$V_{ppv} = kD^{-b} \tag{1}$$

where V_{ppv} is peak particle velocity (PPV) in (mm/s); D, the scaled distance in $(\frac{m}{kg^{0.5}} or \frac{m}{kg^{0.33}})$ which is the ratio of distance of monitoring point from the geometric center of the blasting area, R in (m) to maximum charge per delay, W in (kg); k and b are site specific constants which describe the characteristic of propagating media, blast design and geology.

Many research workers have contributed towards the in-depth understanding of some of the controllable and non-controllable parameters pertaining to blast induced ground vibration (BIGV). There are various other empirical models similar to Eq. (1). A summary of some empirical models is listed in Table 1.

An overview of the literature revealed that various factors govern the intensity of BIGV which can be termed as controllable parameters and non-controllable parameters,[13] as mentioned in Table 2. It was agreed that the maximum charge per delay, delay period, blast geometry and distance of monitoring location are the governing factors pertaining to PPV at any point of interest.[6,14] The effect of burden was first studied by Bergmann et al.[15] by blasting the granite rock and the resulting vibrations were measured with the help of pressure gauges. However, no solid conclusion could be drawn from this study. Blair[16] illustrated how the delay interval between blast holes can be chosen to

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Table 1
Summary of various PPV prediction models.

Sl. No.	Reference	Empirical models
1.	Duvall and Petkof[2]	$V_{ppv} = k\left(\frac{R}{\sqrt{W}}\right)^{-b}$
2.	Langefors and Kihlstrom[3]	$V_{ppv} = k\left(\frac{W}{R^{\frac{2}{3}}}\right)^{\frac{b}{2}}$
3.	Ambraseys and Hendron[4]	$V_{ppv} = k\left(\frac{R}{\sqrt[3]{W}}\right)^{-b}$
4.	IS: 6922[5]	$V_{ppv} = k\left(\frac{R^{\frac{2}{3}}}{W}\right)^{-b}$
5.	Ghosh and Daemen[6]	$V_{ppv} = k\left(\frac{R}{\sqrt{W}}\right)^{-b} e^{-\alpha R}$
6.	Ghosh and Daemen[6]	$V_{ppv} = k\left(\frac{R}{\sqrt[3]{W}}\right)^{-b} e^{-\alpha R}$
7.	Roy[7]	$V_{ppv} = n + k\left(\frac{R}{\sqrt{W}}\right)^{-1}$
8.	Bilgin et al.[8]	$V_{ppv} = k\left(\frac{R}{\sqrt{Q}}\right)^{-b} * B^{\gamma}$
9.	Rai and Singh[9]	$V_{ppv} = kR^{-b}W^{a}e^{-\alpha R}$
10.	Ak and Kounuk[10]	$V_{ppv} = k\left(\frac{R}{\sqrt{W}}\right)^{-b} \lambda^{\alpha}$
11.	Simangunsong and Wahyudi[11]	$V_{ppv} = k\left[(1 + cos\theta_i + N_c)\frac{R}{\sqrt{Q}}\right]^{-b}$
12.	Kumar et al.[12]	$V_{ppv} = \frac{{f_c}^{0.642} D^{-1.463}}{\gamma}$, $V_{ppv} = \frac{(0.3396 * 1.02^{GSI} GSI^{1.13})^{0.642} D^{-1.463}}{\gamma}$

Table 2
Controllable parameters and non-controllable parameters affecting BIGV.

Controllable Parameters		Uncontrollable Parameters
Blast Design Parameters	Explosive parameters	Geotechnical and Geo-mechanical parameters
• Hole diameter • Hole depth • Bench height • Burden • Spacing • Stemming • Sub drilling • No. of holes and rows • Hole inclination	• Explosive type • Maximum charge per delay • Charge per hole • Total charge • Powder factor • VOD • Delay time • Direction of initiation	• Rock mass strength • Ground water condition • Discontinuity frequency • Bedding plane

control and minimize the vibration energy within the structural response band of most houses. Induced vibrations were found to be dependent upon the accuracy of the delay initiators as well as the level of random fluctuations between each blast hole signature. Bilgin et al.[8] carried out an extensive study in a lignite mine in order to eliminate environmental influences as a result of blasting. The authors made a reassessment by adding burden (B) as a parameter to classical particle velocity prediction models and came to a conclusion that there was 1–20% recovery in the regression coefficient. Blair[17] depicted that how the separate influence of variables, like weight and type of explosive used per delay, the delay time sequence, scatter in that sequence, spatial pattern of blastholes and properties of the transmitting medium, may be analyzed using a Monte Carlo model that has a predictive power superior to that of the traditional charge weight scaling laws. Blair and Armstrong[18] pointed out that the ground vibrations are affected by the condition of rock mass surrounding the blast hole and the vibrations were found to be independent of burden. Uysal et al.[19] exclusively investigated the effect of burden on blast induced vibration on open pit mines and discovered that burden width had a significant impact on PPV. It was proved that vibration reduces as burden increases. Ak and Kounuk[10] quantified the effect of discontinuity frequency (λ) in the attenuation of PPV. Elevli and Arpaz[20] evaluated the contribution of different parameters on PPV using relation diagram method (RDM). They concluded that the effective parameters for the ground vibration at the point of blast were explosive amount per delay, burden and stemming and in order to reduce the amount of vibration the same parameters should be modified. Blair[21] extensively studied the dependency of PPV on charge length analytically. It was concluded that the peak vibration measured underground due to underground blasting was not significantly dependent on charge weight and this was consistent with model predictions for an infinite visco-elastic medium. However, the peak vibration measured at the surface and due to surface blasting was found to strongly depend upon charge weight, due to geological influences such as near-surface layering. Görgülü et al.[22] investigated the effect of blast design parameters and rock properties using artificial neural network (ANN) and concluded that artificial intelligence methods give better prediction vis-à-vis the empirical models. Simangunsong and Wahyudi[11] estimated the effect of number of coal layer (N_c) between blasting area and monitoring point and incident angle on PPV. Kumar et al.[12] considered the effect of rock mass properties UCS (f_c), unit weight (γ), RQD, GSI on PPV.

A close look at the literature suggests that various efforts have been invested to study the parameters that affect blast induced ground vibrations and utilize them to predict peak particle velocity. However miniature effort have been taken to quantify the effect of blast design parameters even though it is a controllable parameter and it governs ground vibrations markedly. This has been found to be still debatable whether ground vibrations, in terms of peak particle velocity, is influenced by burden, one of the blast design parameters, or not. Therefore, the need has been felt to study the influence of burden as blast design parameter (if any) in evaluating vector peak particle velocity (VPPV). Further, in order to account for the variability of parameters influencing VPPV, a need has also been felt for a probabilistic analysis. In view of this, in the present work, an attempt has been made first to propose a model for prediction of VPPV employing multiple regression analysis of 10 different mining sites in India and Turkey. The parameters like burden, maximum charge per delay and monitoring distance have been used to develop the VPPV predictive equation. Subsequently, a probabilistic analysis has been carried out with the help of Monte-Carlo simulations on proposed model.

2. Data acquisition

For the development of an empirical model, blast data have been collected from the literature pertaining to ten different open cast mining sites: seven from India and three from Turkey. Details of the data are summarized in Table 3. The data set for Chittorgarh Mines and six other mine sites[22] in India are shown in Figs. 1–7 as VPPV vs. scaled distance plot for various values of the burden. The data pertaining to Turkey sites can be obtained from respective publications as mentioned in Table 3 and therefore have not been presented here.

3. Deterministic analysis: empirical model

To develop an empirical model for determination of vector peak particle velocity (VPPV), first of all an attempt has been made to identify the parameters influencing VPPV. Critical review of literature suggests that maximum charge per delay (W) and monitoring distance (R) are the two basic parameters significantly affecting the vector peak particle velocity. As mentioned above, there are both the thoughts exist in literature. Few research workers state that VPPV is independent of burden and some of the research workers concluded that burden also influences VPPV. In view of this, the data has been analyzed to obtain the expressions for VPPV in two manners: once by considering the burden (model 1) and another by not taking the burden into account (model 2) while analyzing the data.