A new predictor for ground vibration prediction and its comparison with other predictors

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In surface mining, explosives in huge quantity are being used for fragmenting the rock mass but only a part of the explosive energy is used in doing the useful work, the rest is spent in redundant phenomena such as ground vibrations, noises and air blasts. The elastic energy which is at a level less than the energy required to break the rock, gives rise to ground vibration. Airblast occurs when the gases produced during blasting escape to the atmosphere through existing weakness planes or rock displacement. Ground vibration and airblast both are matter of great concern as it causes damage to the existing surface structures and nuisance to the residents in the closer vicinity of the mine. It attracts more attention as the mines are approaching near exceedingly populated areas. A number of vibration predictors have been proposed which can be used to calculate the safe charge that can be initiated per delay, with minimum spoil to environmental. An attempt has been made to propose a new vibration predictor to calculate the safe charge per delay more precisely. Its results are compared with other predictors also. A program has been developed for analyzing the data from the field observations. A large number of blast data with wide variation in physico-mechanical properties were collected and analyzed to perceive the accuracy and applicability of the proposed predictor equation.

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Blasting is still cheapest and economical method of rock mass excavation. On detonation of explosive charge in a blast hole, huge quantity of gaseous and pressure energy is liberated spontaneously. However, only a small part of this energy is utilized for fragmenting and displacing the rock, while the rest of it is wasted in the form of ground vibrations, air blasts, and noise and fly-rocks. Ground vibrations produced due to blasting affect both the structures around the blast site as well as the structures existing in the closed vicinity. It may cause damage to the structures and buildings and is a nuisance for the living beings in the area. The affect of ground vibration depends upon its magnitude and frequency which are based on the blast design, blasting pattern, explosive properties, local geology, structural discontinuities and physico-mechanical properties of the rock mass.

When an explosive charge is detonated in a confined hole, a large volume of gases at high pressure and temperature produced. In the process of blasting, chemical energy of explosive is converted into heat and mechanical energy and resulted into flow, crushing and fracturing the surrounding rock mass up to a limit. As the shock wave propagates further into the rock mass its intensity drops down and unable to cause any permanent deformation. This phenomenon in ground disturbance is known as ground vibration. When an explosive detonates in the blasthole, approximately 20-30% of the energy is only utilized in fragmenting the rock and a portion of the energy is lost in the form of vibration waves through the ground. A part of the energy is also dissipated in the air which produces noise. Almost 90% of the earth borne energy reaches the surface a few meters from the total displacement area and acts as surface waves\textsuperscript{1,2}. Whenever blast vibration occurs; it vibrates the ground with certain velocity and imparts to it certain amount of acceleration. When ground vibrates, the lower part of the structure moves with the ground but upper parts lag behind, this result in deforming a rectangular shape into a parallelogram which has one diagonal elongated and other compressed. When elongation exceeds the strength of the material, cracks develop. The opposite diagonal is elongated when the ground vibration reverses. As vibration waves pass under a structure, the structure is lifted up and down and moved from side to side and back and forth.

The ground vibration is a wave motion; spreading outward from the blast like ripples spreading outwards due to impact of stone dropped into a pond of water. When an explosive detonates, a solid
material to a gaseous material and this spontaneously generates shock and ground vibration. The vibration radiates from the blast hole at a speed controlled by the surrounding rock mass. As the vibration passes surface structures, it induces vibration in those structures. These vibrations induce a resonance in the structures and the amplitude of the resonance may exceed the amplitude of the initial ground vibrations. The relative amplitudes of ground vibration and induced structural vibration depend largely on the match between frequency of ground vibration and the natural frequency of the structure\(^3\). The components of ground motion can affect the buildings and other surface structures through compression and tension and through vertical and horizontal shearing effects (Fig. 1).

**Vibration Predictor Equations**

The increasing demand of minerals lead enormous consumption of explosive and the problem of ground vibration requires special attention. There are number of vibration predictors proposed by various researchers. On single predictor equation cannot fully satisfy all the variation in the observation field data. It is essential to compare the results obtained by the different vibration predictors for the same data sets.

**USBM equation**

Duval and co-workers\(^5\) of the US Bureau of Mines concluded that any linear dimension be scaled with the square root of the charge weight. The corresponding relationship assumes the form

\[
v = K \left( \frac{R}{\sqrt{Q_{MAX}}} \right)^{-B}
\]

(1)

where, \(v\) is peak particles velocity, \(K\) and \(B\) are site constants to be determined by regression analysis, \(R\) is distance of the measuring transducer from the blasting site (m) and \(Q_{\text{max}}\) maximum charge per delay (kg).

**Ambraseys-Hendron\(^7\)**

\[
v = K \left( \frac{R}{Q_{MAX}^{1/3}} \right)^{-B}
\]

(2)

**Langefors-Kihlstrom\(^8\)**

\[
v = K \left( \frac{Q_{MAX}}{R^{2/3}} \right)^B
\]

(3)

**Indian Standard predictor equation**

The empirical relationship suggested by Indian Standard\(^9\) uses the concept in which blast is scaled to the equivalent distance to scaled distance, defined as the charge weight divided by cube root of the square of actual distance. The relationship is expressed in the form

\[
v = K \left( \frac{Q_{MAX}}{R^{2/3}} \right)^B
\]

(4)

**General empirical equation**

The most common form of equation to predict the ground vibration level at any distance from a blast hole to series of blast hole has the general form\(^10, 11\)

\[
v = K . R^{-B} . Q_{MAX}^A
\]

(5)

where, \(K\), \(B\) and \(A\) are empirical constants, which can be determined by multiple regression analysis of two independent variables.

**Ghosh-Daemen modification**

Ghosh and Daemen\(^12\) recommended that inelastic attenuation causes energy losses during wave propagation. This inelastic effect leads to a decrease in amplitude in addition to those due to geometrical spreading. They reformulated the propagation relations of USBM in terms of the peak particle velocity (v) maximum charge per delay (\(W\)), distance

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*Fig. 1—Ground vibration due to blasting*
of the measuring transducer from the blast face \((D)\) and inelastic attenuation factor \((\alpha)\). The modified equations are:

GHDN1:

\[
v = K \left( \frac{R}{\sqrt{Q_{\text{MAX}}}} \right)^{-B} e^{-\alpha R} \quad \ldots (6)
\]

GHDN2:

\[
v = K \left( \frac{R}{\sqrt{Q_{\text{MAX}}}} \right)^{-B} e^{-\alpha R} \quad \ldots (7)
\]

CMRI predictor equation

The predictor model developed by Central Mining Research Institute\(^{13}\) assumes special significance because of its simplified form and the zone of disturbances due to blasting. The equation is valid only in the zone of disturbance (when \(Q_{\text{max}} > 0, \quad \nu > 0\)).

\[
v = n + K \left( \frac{R}{\sqrt{Q_{\text{MAX}}}} \right)^{-1} \quad \ldots (8)
\]

Proposed equation

The proposed equation predicts the Peak Particles Velocity (PPV) levels at any distance from the blasthole. Ghosh and Daemen\(^{12}\) suggested that inelastic attenuations cause energy losses during the wave propagation only. In the proposed equation we have considered both cases like elastic and non-elastic attenuation.

\[
v = K.R^{-B} Q_{\text{MAX}}^A e^{-\alpha R} \quad \ldots (9)
\]

In Eq. (9), \(\alpha\) is an energy factor. It is dependent on the medium through which wave passes. When the wave spread away from the source absorption and partition of interfaces took place resulted into the deceases of energy factor. The elastic energy associated with motion is gradually absorbed by the medium.

To validate the new predictor a computer program is developed to analysis the blast data from the field observations. The safe charge per delay, distances from blast site to monitoring point and peak particle velocity are taken as input parameters. The out puts are the value for different coefficients. In the second phase, the program provided safe charge at different distances for a particular PPV. Thus, the safe charge per delay is made available to the users from different predictor. The user can select the values depending upon the equation adopted. Further, the safe charge/delay versus scaled distance curve is plotted using different equations.

Results and Discussion

A wide variety of vibration data from different mines having difference physico-mechanical properties were analyzed using the software package. To verify the proposed predictor equation three rock types were taken such as dolomite (43 data), limestone (95 data) and sandstone (95 data), to understand that up to which degree the predictors are site specific. Based on the analysis of frequency of variation and threshold standards, a value of 10 mm/s is considered as safe for general structures. The various site constants depicted from different predictors’ equations are given in Tables 1-3. This shows that the observed values are closer to which particular predictor equation. For better comparison of all predictors’ equation, coefficient of correlation \((R)\) is also calculated.

In the proposed predictor equation, an inelastic attenuation factor \(e^{-\alpha R}\) is added. Among these predictors, the proposed predictor equation gives better correlation coefficient \((R)\) in two cases and in one case CMRI predictor gives slightly better value of \(R\). It exhibits that the predictor equation should be site specific. It infers that energy density is mainly proportional to the first power of the density of the medium and second power of the frequency and amplitude of the vibration waves.

Case 1: Limestone

In the first case, vibrations were recorded in limestone mines. The rockmass belongs to the pre-cambrian formation associated with shale, quartzite and phyllites. Limestone is fine grained, massive, hard, compact and micro-crystalline. The limestone beds were blasted having spacing 2-4.4 m, burden 2-8 m, hole diameter 100-150 mm, number of holes 25-80 and hole depth 2.5-11 m in a single round of blast.
The site constant and coefficient of the predictor equation have been determined by the least square method of regression analysis (Table 1). In this case, the proposed predictor gives better correlation coefficients ($R$) than other predictors. The variation of safe charge per delay with distance as obtained from different predictor’s equation is shown in Fig. 2. It shows that the Indian and Langefors-Kihlstrom predictor gives low safe charge/delay; however, proposed, CMRI and USBM compute normal safe charge/delay. General, Ambraseys–Hendron and Ghosh-Daemen shows a very sharp increase in safe charge/delay (Fig. 2). The safe charge/delay obtained by the proposed predictor is also plotted with varying distance on the different PPV (Fig. 3).

Case 2: Dolomite

Blast vibrations data were recorded from a dolomite quarry. The dolomite is grey or cream in colour, hard, compact, massive and fined grained. It is highly jointed and fissured, filling with clayey material encountered along the joint planes. Such filling are common on top beds however, they are sporadic expect at depth with some solution cavities. The blast parameters are spacing (1.5-3.0 m), burden...
(2.8-3 m), hole diameter (100-115 mm), number of holes 10-45 and hole depth (3-7.5 m) in a single round. The site constants and correlation coefficient of the predictor equation have been determined (Table 2). In this case, the CMRI predictor equation gave little higher $R$ than other predictor’s like to proposed, USBM, Ghosh-Daemen. The variation of safe charge per delay with distance as calculated from the different predictor’s is shown in Fig. 4. It indicates that the Indian and Langefors–Kihlstrom predictor equations gave low safe charge/delay whereas, proposed, CMRI and USBM compute normal safe charge/delay. The general, Ambraseys–Hendron and Ghosh-Daemen shows a very sharp increase in the safe charge/delay (Fig. 4).The safe charge by proposed predictor is also plotted with assorted distance at different PPV (Fig. 5).

**Case 3: Sandstone**

Blast induced ground vibration data were collected from sandstone bench of an opencast mine. The rock litho-units belong to barakar formation. A thick cover of soil blankets the area and as such there is no exposures of rock expect for a few detached and scanty exposure along the nalla. The blast parameters are: spacing 2-2.2 m, burden 9-10 m, hole diameter 100-300 mm, number of holes 90, hole depth 4.8-35 m in a single round of blast. The site constants and coefficient of correlation of the predictor equation have been determined (Table 3). In this case, the proposed predictor gives higher $R$ than other predictor’s like USBM, General and Ghosh–Daemen. The variation of safe charge per delay with distance as calculated from different predictor’s equation is revealed in Fig. 6. It shows that the Indian and general predictor equation give low safe charge/delay whereas, proposed, CMRI, Langefors-Kihlstrom, Ghosh-Daemen1 and USBM compute normal safe charge/delay. The general, Ambraseys-Hendron and Ghosh-Daemen2 gives a very sharp increase in safe charge/delay (Fig. 6). The safe charge/delay is also plotted with distance on different PPV by proposed predictor (Fig. 7).

**Analysis of safe charge per delay**

Safe charge per delay is calculated using all the predictors and its correlation coefficient are tabulated for all the three cases used for evaluation of proposed

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### Table 3

<table>
<thead>
<tr>
<th>Equations</th>
<th>K</th>
<th>B</th>
<th>A</th>
<th>$\alpha$</th>
<th>n</th>
<th>r</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>USBM</strong></td>
<td>398.3117</td>
<td>1.539059</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0.8577</td>
</tr>
<tr>
<td><strong>Amb-Hend</strong></td>
<td>984.4586</td>
<td>1.337295</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0.8563</td>
</tr>
<tr>
<td><strong>Gh-Dae2</strong></td>
<td>1342.912</td>
<td>1.463612</td>
<td>–</td>
<td>-0.00023</td>
<td>–</td>
<td>0.8601</td>
</tr>
<tr>
<td><strong>CMRI</strong></td>
<td>304.0585</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>-14.3927</td>
<td>0.8393</td>
</tr>
<tr>
<td><strong>Proposed</strong></td>
<td>713.2291</td>
<td>-1.46311</td>
<td>0.607387</td>
<td>1.47E-05</td>
<td>–</td>
<td>0.8684</td>
</tr>
<tr>
<td><strong>Lang–Kihl</strong></td>
<td>74.52602</td>
<td>1.968325</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0.7699</td>
</tr>
<tr>
<td><strong>Indian std.</strong></td>
<td>9.300723</td>
<td>0.04155</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0.2850</td>
</tr>
<tr>
<td><strong>General</strong></td>
<td>1319668</td>
<td>1.457594</td>
<td>-0.60831</td>
<td>–</td>
<td>–</td>
<td>0.8644</td>
</tr>
<tr>
<td><strong>Gh-Dae1</strong></td>
<td>329.4727</td>
<td>1.401318</td>
<td>–</td>
<td>0.000254</td>
<td>–</td>
<td>0.8602</td>
</tr>
</tbody>
</table>

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Fig. 4—Variation of safe charge per delay with distance from different predictors equation based on 10mm/s vibration level (dolomite)

Fig. 5—Variation of safe charge per delay with distance from proposed predictor (dolomite)
predictor (Table 4). It exhibits that proposed predictor gives better safe charge per delay, which is near to the observed values from the field. Other predictor’s like USBM, Langeors–Kihlstrom and CMRI shows good correlation. Figs 8-10 shows the relation between observed and predicted values using 95% confidence level.

Table 4—The coefficient of correlation from all predictor equations.

<table>
<thead>
<tr>
<th>Rocks type Equations</th>
<th>Coefficient of correlation (r)</th>
<th>Dolomite</th>
<th>Limestone</th>
<th>Sandstone</th>
</tr>
</thead>
<tbody>
<tr>
<td>USBM</td>
<td>0.6998</td>
<td>0.3970</td>
<td>0.7367</td>
<td></td>
</tr>
<tr>
<td>Lang–Kihl</td>
<td>0.7222</td>
<td>0.4034</td>
<td>0.7586</td>
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<tr>
<td>Indian std.</td>
<td>0.6603</td>
<td>0.2626</td>
<td>0.1532</td>
<td></td>
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<tr>
<td>Gh-Dae2</td>
<td>0.6444</td>
<td>0.3243</td>
<td>0.6408</td>
<td></td>
</tr>
<tr>
<td>CMRI P.</td>
<td>0.6016</td>
<td>0.4087</td>
<td>0.6971</td>
<td></td>
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<tr>
<td>General.</td>
<td>0.6963</td>
<td>0.1806</td>
<td>0.1925</td>
<td></td>
</tr>
<tr>
<td>Proposed</td>
<td>0.7289</td>
<td>0.5911</td>
<td>0.7028</td>
<td></td>
</tr>
<tr>
<td>Amb-Hend</td>
<td>0.6563</td>
<td>0.3235</td>
<td>0.6477</td>
<td></td>
</tr>
<tr>
<td>Gh-Dae1</td>
<td>0.7123</td>
<td>0.4746</td>
<td>0.7292</td>
<td></td>
</tr>
</tbody>
</table>
Conclusions

The 220 vibration data sets were used for validation of proposed predictor equation. It is found that different predictors give a wide range of correlation coefficients. The calculated and observed values have also wide variation. Few predicted and observed values shows close relation for particular equation. It is clear that a large number of factors influence the ground vibration characteristics and more factors (variable) are included to get more reliable predictor.

Every predictor equation has limitations and utilities. It is also seen that one cannot relies on only one predictor to calculate the safe charge per delay.

The proposed equation gives better correlation coefficient in two cases. Some more analysis is required to generalize but it reveals that, if input variables influencing output goals are clearly acknowledged and a descent number of eminence data are available, it can be effectively used for prediction of safe charge for minimizing the damage.

Reference