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Determination of blast-induced ground vibration equations for rocks using mechanical and geological properties

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ABSTRACT

In the recent decades, effects of blast loads on natural and man-made structures have gained considerable attention due to increase in threat from various man-made activities. Site-specific empirical relationships for calculation of blast-induced vibration parameters like peak particle velocity (PPV) and peak particle displacement (PPD) are commonly used for estimation of blast loads in design. However, these relationships are not able to consider the variation in rock parameters and uncertainty of in situ conditions. In this paper, a total of 1089 published blast data of various researchers in different rock sites have been collected and used to propose generalized empirical model for PPV by considering the effects of rock parameters like unit weight, rock quality designation (RQD), geological strength index (GSI), and uniaxial compressive strength (UCS). The proposed PPV model has a good correlation coefficient and hence it can be directly used in prediction of blast-induced vibrations in rocks. Standard errors and coefficient of correlations of the predicted blast-induced vibration parameters are obtained with respect to the observed field data. The proposed empirical model for PPV has also been compared with the empirical models available for blast vibrations predictions given by other researchers and found to be in good agreement with specific cases.

1. Introduction

A blast generates ground shock and vibration which may cause damage to the surrounding structures. In the recent decades, blast-induced ground shocks and their propagation in rock mass have been drawing more and more attention. The blast effects include change in rock behavior having implications on the stability and integrity of structures. Structures are designed and constructed to bear static and dynamic loads in addition to taking care of settlement of foundations within permissible limits. Dynamic loads include earthquake load, vibratory machine load, blast load, etc. The blast load on structures is caused by quarrying, mining activities, accidental explosion of underground explosives, terrorist attacks, excavation activities, etc. There are complexities in the wave and ground motion characteristics, blasting parameters and site factors. Various experimental site-specific studies have been performed to predict and control blasting effects. The parameters associated with the vibration are displacement, velocity and acceleration with their respective frequencies. It has been inferred from literature that peak particle velocity (PPV) is generally a good index of damage to structure (IS 6922, 1973; Monjezi et al., 2010; Kumar et al., 2012). The vibration level at a distance depends on charge per delay, vibration frequency, rock characteristics (type, unit weight, layering, slope of layers), blast hole conditions, presence of water, propagation of surface and body waves in the ground, and to a lesser extent on method of initiation. Fractures are developed in rocks due to tensile and shear stresses. Hence, studies of blast-induced ground vibrations in rocks have become important.

The relationship between PPV and scaled distance (D) can be written as

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

where v is the PPV (m/s); D is the scaled distance (m/kg$^{1/2}$), which is defined as the ratio of distance from charge point, R (m), to the

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square root of charge mass, Q (kg), expressed in TNT net equivalent charge weight, i.e. $D = R/Q^{1/2}$; k and b are site constants.

Generally, site constants k and b are determined by blast experiments. In the absence of field blast data, empirical models are used to evaluate these constants. There are various empirical models similar to Eq. (1), developed by various researchers for different rock and soil sites (Kumar et al., 2014a,b) on the basis of blast data. A summary of various researchers' (Nicholls et al., 1971; Ghosh and Daemen, 1983; Pal Roy, 1993) models in rock sites that are available in the literature is reported by compiling a total of 23 different blast vibration prediction models which are listed in Table 1. These site-specific empirical equations cannot be generalized for use at other sites. Though there is significant scattering of blast data of researchers, each model gives a fair prediction of PPV values at the corresponding site. Any available site PPV model does not accurately predict PPV for other sites.

Effects of various rock characteristics on PPV have been studied in the past by a few researchers. Effects of rock discontinuities on blast wave propagation were presented by Ak and Konuk (2008), Kuzu (2008), UFC 3-340-02 (2008), etc. Effects of different rock formations on prediction model were analyzed by Nateghi (2011). Rock formation differences included changes in thickness, dip of layers, aperture of major joints and bedding, etc. Particle velocity is less sensitive to change in geological conditions than acceleration or displacement, hence it is more consistent and predictable (Nateghi, 2011). Effects of rock joints on blast-induced wave propagation have been studied by Wu et al. (1998) and Hao et al. (2001). Particle models have been used to model static tests of rough undulating rock joints in shear (Kusumi et al., 2005). Vibration attenuates fastest if it propagates in the direction perpendicular to the rock joint set. Presence of water table and soil-rock interface affects the slope of attenuation curve (UFC 3-340-02, 2008). PPV formula suggested by IS 6922 (1973) depends on the types of rock. PPV characteristic was investigated on soil ground surface, soil-rock interface and rock free field for a site by blast test program (Wu et al., 2003). It was observed that PPV on soil surface was higher than that at the soil-rock interface for the same scaled distance. Nicholls et al. (1971) pointed out that, in case of massive rock or horizontally stratified rock, there is little difference in wave propagation with direction, and in case of anisotropy and geological complexity, wave propagation may differ with direction. The data

Table 1
Summary of various researchers' models.

No.	Researchers	Empirical models
1	Duvall and Petkof (1959)	$v = k(R/Q^{1/2})^{-b}$
2	Langefors and Kihlstrom (1963)	$v = k(Q/R^{2/3})^{b/2}$
3	Ambraseys and Hendron (1968)	$v = k(R/Q^{1/3})^{-b}$
4	Nicholls et al. (1971)	$v = 0.362D^{-1.63}$
5	IS 6922 (1973)	$v = k(Q^{2/3}/R)^{1.25}$
6	Siskind et al. (1980)	$v = 0.828D^{-1.32}$
7	Ghosh and Daemen (1983)	$v = k(R/Q^{1/2})^{-b}e^{-\alpha R}$
8	Ghosh and Daemen (1983)	$v = k(R/Q^{1/3})^{-b}e^{-\alpha R}$
9	Pal Roy (1991)	$v = n + k(R/Q^{1/2})^{-1}$
10	Pal Roy (1991)	$v = n + k(R/Q^{1/3})^{-1}$
11	CMRI (1993)	$v = n + k(R/Q^{1/2})^{-1}$
12	Kahriman (2002)	$v = 1.91D^{-1.13}$
13	Kahriman (2004)	$v = 0.34D^{-1.79}$
14	Kahriman et al. (2006)	$v = 0.561D^{-1.432}$
15	Rai and Singh (2004)	$v = kR^{-b}Q_{max}e^{-\alpha}$
16	Nicholson (2005)	$v = 0.438D^{-1.52}$
17	Rai et al. (2005)	$Q_{max} = k(vD^2)^b$
18	Ozer (2008) (sandstone)	$v = 0.257D^{-1.03}$
19	Ozer (2008) (shale)	$v = 6.31D^{-1.9}$
20	Ozer (2008) (limestone)	$v = 3.02D^{-1.69}$
21	Ak et al. (2009)	$v = 1.367D^{-1.59}$
22	Badal (2010)	$v = 0.29D^{-1.296}$
23	Mesec et al. (2010)	$v = 0.508D^{-1.37}$

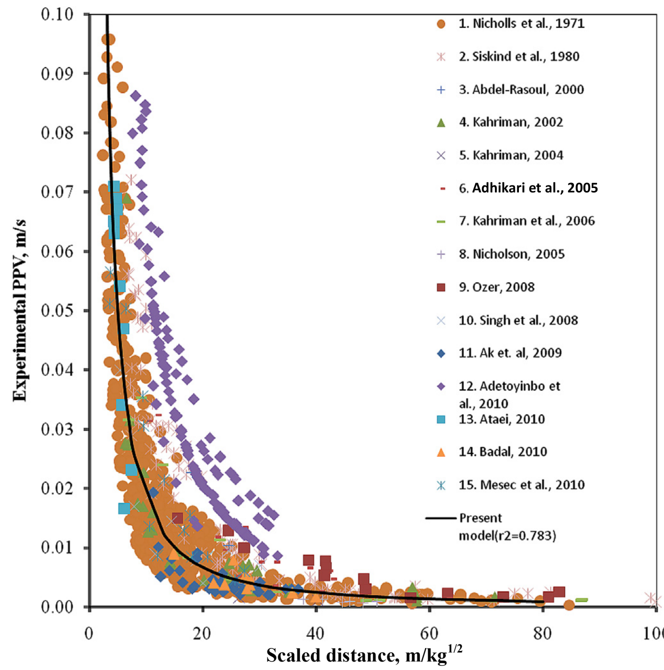

Fig. 1. Experimental PPV as a function of scaled distance.

from tests in 12 limestone and dolomite quarries almost showed scattering of a factor of 3 (Nicholls et al., 1971). Geology can have a major effect on both amplitude level and decay with distance (Nicholls et al., 1971). Effect of Young's modulus and P-wave velocities on PPV was studied by Singh et al. (2008). Higher P-wave velocity generates larger ground vibration. If the Young's modulus of rock is high, then less attenuation and loss of energy occur, thus there is an increase in ground vibration. Analysis of pore water pressure increases in soil and rock from underground explosions has been presented by Charlie et al. (1996). Effect of Hoek's geological strength index (GSI) was studied by Ozer (2008) and Mesec et al. (2010). Applicability of rock mass quality for design of blasting arrangements at various stages of excavation was discussed by Adhikari et al. (1999). A PPV model was developed by incorporating rock properties like Poisson's ratio, Young's modulus, P-wave velocity, etc., by Khandelwal and Singh (2006, 2009) using artificial neural network (ANN). Blast hole depth and stemming were incorporated in PPV model using ANN by Monjezi et al. (2011). Effects of rock strength parameter on blast were studied by Chakraborty et al. (1998). Effects of rock type, rock density, stratification, etc., were studied by ISRM (1992). Various studies on PPV were carried out with respect to safety of structures and personnel. Relationship between PPV on the surface structure and PPV at the foundation level was studied by Pal Roy (1998). The minimum safe distance of throw of fragments caused by blast is specified by various codes. Influence of blast design parameters on flyrock distance was studied by Adhikari (1999). Radius of danger zone for flyrock generated from blast is specified as 500 m by DGMS (1982). Uniaxial compressive strengthen (UCS) and density have no much change in a small area of blast. ANN was used to estimate the specific charge in various conditions of tunnel blasting by Alipour et al. (2012). A blast test program was carried out for prediction of liquefaction in the case of deep foundation by Ashford et al. (2004). Behavior of piles subjected to blast-induced lateral spreading was assessed by Ashford et al. (2006).

It is clear from the above analyses that effects of various rock characteristics on PPV model have been studied by various researchers. However, effects of important engineering properties of rock, e.g. unit weight, UCS, rock quality designation (RQD) and GSI, on PPV prediction model have not been studied yet. But these rock properties affect the blast wave propagation extensively. Hence, there is a need to develop a PPV model which includes these important engineering rock properties.

This paper aims to investigate the relationship between PPV and scaled distance for blast in rock sites. An empirical model is proposed for PPV by considering a wide range of published experimental explosions in rock sites. The model includes the contribution of various engineering rock parameters such as unit weight and UCS/RQD/GSI. The development of model is proposed in this paper as follows: (i) Experimental data of various researchers have been collected from the published literature; (ii) Engineering rock parameters affecting blast wave propagation have been collected and assigned to experimental data; (iii) Empirical model has been developed.

2. Establishment of equation for PPV

2.1. Published field blasts

A total of 1089 published field blast data by 13 different researchers were collected. The data were available in terms of PPV and scaled distance for various types of rocks. To assess the PPV, experimental values of PPV are plotted against scaled distance for the available experimental data of different researchers. Fig. 1 shows the plot of experimental PPV as a function of scaled distance for experimental studies. The data in the figure are presented by different symbols to represent different experimental studies. All empirical models are plotted in Fig. 2 for comparison purpose. It is observed from Fig. 1 that there is a sudden decrease in PPV for scaled distance up to 8 m/kg$^{1/2}$. Site-specific empirical relationship between PPV and scaled distance was developed after analysis of experimental data. The investigations pertaining to the collected data are explained briefly as follows.

Nicholls et al. (1971) analyzed the ground vibration results of a blasting program over a 10-year period by the U.S. Bureau of Mines. Data from 171 quarry blasts at 26 different sites were presented by

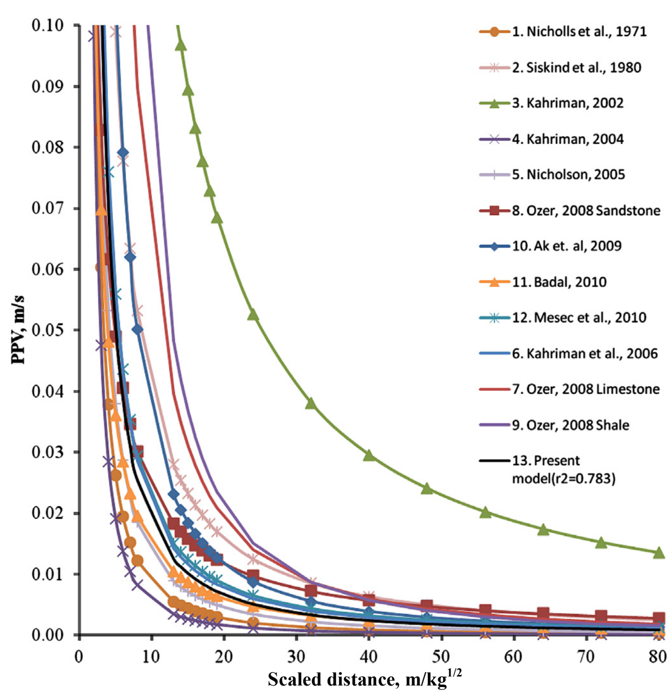

Fig. 2. Comparison of various empirical models.

them. Siskind et al. (1980) analyzed vibration data from surface mining blasts. Structural responses to ground vibration were measured in 76 sites from 219 production blasts. Direct measurements of structural responses at various locations in 76 sites in terms of structural motion (in/s) were taken. Abdel-Rasoul (2000) provided propagation laws for ground vibrations and air blasts after measurement and evaluation of ground vibration levels and air blast overpressures induced by blasting at the limestone quarries in Egypt. Kahriman (2002) analyzed the results of ground vibration measurements induced by bench blasting at Can Open-pit Lignite Mine in Turkey for 54 blast events. Kahriman (2004) analyzed vibration components for 73 blast events at a limestone quarry located in Istanbul, Turkey. An empirical relation between PPV and scaled distance was developed by Kahriman et al. (2006) based on measurement of vibration caused by bench blasting in an open-pit mine in Turkey. Nicholson (2005) compared Office of Surface Mines (OSM) standard with blast field data at Bengal Quarry, Jamaica. Ozer (2008) presented and analyzed results of ground vibration induced by blasting during construction of metro tunnel at Istanbul, Turkey. 659 blast events were recorded in 260 shots. Rock types were sandstone, shale and limestone. Singh et al. (2008) used adaptive neuro–fuzzy interface system (ANFIS) model to predict the PPV and frequency using blast design, rock properties and explosive parameters from the Northern Coal Field open-pit mine in Madhya Pradesh, India. Ak et al. (2009) presented and analyzed the results of ground vibration measurement induced by 43 bench blasting events at an open-pit mine consisting of older metamorphic rocks in Turkey. Badal (2010) analyzed data of blasting operations at open cast coal mines in Rairarh, Chhattisgarh, India. Mesec et al. (2010) analyzed vibration measurements at the trial, construction and quarry blasting in sediment rock deposits in Croatia. Construction and quarry blasting were carried out in sediment rock deposits, namely limestone and dolomite.

2.2. Assigning rock properties to collected data

The rock properties from various sources, e.g. Bowles (1997), Hoek et al. (1998), have been collected and presented in Table 2. It is observed from this table that in most of the cases, single value of unit weight is provided. For other cases, range of unit weight is provided which is very close. Thus the average value of unit weight is assigned in these cases. The reasons for selection of particular values for various sites are explained in the following section. Assigned values of unit weight and UCS can be varied to investigate the effects of these parameters on PPV. For this purpose, reliability study is needed. But in this paper, it is not covered.

UCS value is assigned to the data based on their geological descriptions provided by the researchers along with the data, but the average value of UCS is not assigned. Ak et al. (2009) recorded measurements in open-pit magnesite mine comprising Paleozoic-aged metamorphic rocks and tectonically overlying ultramafic rocks. In this mine, magnesium carbonate was produced, which was the alteration product of ultramafic rock, serpentinine, etc., in regional metamorphic terrains. The ultramafic rock is igneous rock with low silica content, and high magnesium and iron content. The Earth's mantle is composed of ultramafic rock. The engineering properties of this rock match with those of schist which is a metamorphic rock. Lower limit of UCS of schist is selected as it satisfies the site condition. Five data of Ozer (2008) were considered which were obtained from the first region of six test sites in sandstone. The formation of the first region was sandstone and the rock unit was greywacke. The upper limit of the range has been selected to suite the site condition. Majority of the lignite bearing series thickness consisted sandstone in case of Kahriman (2002). Average values of unit weight and UCS have been considered from the ranges given in Table 2. The site considered

Table 2
Selection of rock unit weight and UCS from various sources with summary equation with rock properties.

No.	Researchers	Type of rock	Range of properties		Reference of rock properties	Current study		Number of blast data	Equation with rock properties, $v = (f_c^c D^b)/\gamma$. Weighted average $c = 0.642$, $b = -1.463$	
			γ (kN/m^3)	f_c (MPa)		γ (kN/m^3)	f_c (MPa)		c	b
1	Nicholls et al. (1971)	Granite	26.4	70–276	Bowles (1997)	26.4	70	58	0.406	−1.155
2	Nicholls et al. (1971)	Limestone	26	35–170	Bowles (1997)	26	35	145	0.826	−1.682
3	Nicholls et al. (1971)	Diorite	26	100–250	f_c (W1), γ (assumed)	29	100	54	0.597	−1.425
4	Nicholls et al. (1971)	Dolomite	28.5	60–170	γ (W2), f_c (W3)	28.5	60	165	0.563	−1.35
5	Nicholls et al. (1971)	Diabase	28	>250	Hoek et al. (1998)	28	250	116	0.524	−1.376
6	Nicholls et al. (1971)	Schist	26	35–105	Bowles (1997)	26	70	34	0.604	−1.425
7	Nicholls et al. (1971)	Sandstone	22.8–23.6	28–138	Bowles (1997)	23.2	50	58	0.557	−1.338
8	Siskind et al. (1980)	Coal	11–14	4–47	γ (W2) and f_c (W4)	12.5	47	105	0.644	−1.46
9	Siskind et al. (1980)	Ironstone	50.4	150–350	γ (W5), f_c (assumed)	50.4	302	7	0.569	−1.403
10	Abdel-Rasoul (2000)	Limestone	26	35–170	Bowles (1997)	26	170	2	1.346	−2.565
11	Kahriman (2002)	Sandstone	22.8–23.6	28–138	Bowles (1997)	23.2	83	30	0.468	−1.302
12	Kahriman (2004)	Limestone	26	35–170	Bowles (1997)	26	35	4	0.695	−1.698
13	Kahriman et al. (2006)	Schist	26	35–105	Bowles (1997)	26	70	16	0.74	−1.62
14	Nicholson (2005)	Limestone	26	35–170	Bowles (1997)	26	35	7	1.136	−2.054
15	Adhikari et al. (2005)	Coal	12.5	25–50	Hoek et al. (1998)	12.5	50	13	0.662	−1.477
16	Ozer (2008)	Limestone	26	35–170	Bowles (1997)	26	170	7	0.606	−1.388
17	Ozer (2008)	Sandstone	22.8–23.6	28–138	Bowles (1997)	23.2	138	3	0.564	−1.288
18	Ozer (2008)	Shale	18.85	25–100	Hoek et al. (1998)	18.85	100	5	3.542	−4.902
19	Singh et al. (2008)	Coal	11–14	4–47	γ (W2), f_c (W4)	12.5	25	9	0.242	−1.062
20	Adetoyinbo et al. (2010)	Gneiss	27.5	>100	Hoek et al. (1998)	27.5	276	169	0.716	−1.507
21	Ak et al. (2009)	Schist	26	35–105	Bowles (1997)	26	35	39	0.496	−1.285
22	Ataei (2010)	Limestone	26	35–170	Bowles (1997)	26	35	10	1.157	−2.348
23	Badal (2010)	Coal	11–14	4–47	γ (W2), f_c (Bell, 2007)	12.5	25	11	0.6	−1.503
24	Mesec et al. (2010)	Limestone	26	35–170	Bowles (1997)	26	78	22	0.61	−1.382

Note: γ is the unit weight, and f_c is the UCS. W1–W5 are web reference numbers.

by Kahriman (2004) was limestone quarry. Limestone at the site seems to be weak. Hence, lower limit of UCS is selected. Mesec et al. (2010) conducted tests on three different groups of rocks (different locations). Limestone group was considered in the present study. UCS is selected from Table 2 to match the GSI value estimated by the authors. Out of 26 different sites of Nicholls et al. (1971), seven types of rock data have been considered in this study. From the UCS range given in Table 2, lower values for rocks have been taken as they match with the descriptions given in the paper. The unit weight of seven rocks is taken directly from the table. For the site considered by Badal (2010), average values of unit weight and UCS have been taken. For Singh et al. (2008), Siskind et al. (1980), Nicholson (2005) and other researchers, properties were assigned to match the actual rock conditions at site. It is observed in Table 2 that different values of UCS are assigned for the same type of rock as they belong to different sites having different geological conditions.

2.3. Proposed PPV model

Various combinations of two rock properties were tried to fit the equation given by the software CurveExpert 1.37 (Daniel, 2001). By conducting various trial-and-error tests, it was observed that the ratio of some power of UCS and unit weight fitted best with the equation. These parameters were converted into log scale and both were plotted in CurveExpert 1.37, and a linear relationship was established. The summary of equation with two properties is given in Table 2.

It is observed from Table 2 that the powers of UCS (c) and scaled distance (b) were not uniform. Then the weighted mean of the powers were calculated and their final values were obtained. The weighted mean takes into account of number of blast data.

Based on the collected experimental data as shown in Fig. 1, the following empirical model in Eq. (2) with the coefficient of determination, $r^2 = 0.783$, is obtained by the present study to evaluate the PPV. The current model prediction line is also plotted in Fig. 1 along with the collected experimental data.

$$v = \frac{f_c^{0.642} D^{-1.463}}{\gamma} \quad \left(r^2 = 0.783\right) \tag{2}$$

RQD of rocks at various sites is easily available as compared to UCS of rock, f_c. Comparison of RQD with UCS has been given by Bieniawski (1989), as shown in Table 3. Rock conditions representing various ranges of RQD have also been listed in Table 3.

In the present study, random variables, UCS and RQD, are generated due to the scarcity of sufficient experimental data in the literature. Latin hypercube sampling (LHS) technique (Mckay et al., 1979) is adopted herein to generate random samples for the variables. Upper and lower limits of these random variables are known and it is assumed that mean and standard deviation of these random variables are not available, hence uniform distribution is adopted for the variables.

In the current study, the value of f_c varies from 4 MPa to 350 MPa. In the literature, the maximum value of f_c for rocks has been found to be 415 MPa (Bowles, 1997). It has been observed from Table 3 that seven ranges of values are available for both the parameters. Fifty random numbers are generated for each range by assuming the uniform distribution for f_c and RQD, and the data are arranged in ascending order in each range. The minimum value of RQD has been taken as 0, and the minimum and maximum values of f_c have been taken as 0 and 415 MPa, respectively. 350 data points are plotted in Fig. 3 and the best fitting curve was obtained. Two best fit curves have been obtained with $r^2 = 0.992$ and $r^2 = 0.976$, respectively, which are represented by the following equations for different ranges of RQD:

(1) For RQD $\leq$ 75:

$$f_c = 0.59476 RQD + 0.00893 RQD^2 \quad \left(r^2 = 0.992\right) \tag{3}$$

Table 3
Comparison of UCS with RQD and GSI (modified after Bieniawski (1989) and Marinos and Hoek (2000)).

f_c (MPa)	RQD (%) (Bieniawski, 1989)	Rock conditions (Bieniawski, 1989)	GSI (Marinos and Hoek, 2000)	Geological description of rock (Marinos and Hoek, 2000)
>250	90–100	Unweathered wall rock	80–95	Intact or massive structure with very good surface conditions
100–250	75–90	Slightly weathered walls	55–80	Blocky structure with good to very good surface conditions
50–100	50–75	Highly weathered walls	40–55	Very blocky structure with fair to good surface conditions
25–50	25–50	Slicken sided surfaces	25–40	Disturbed structure with poor to fair surface conditions
5–25	<25	Separation>5 mm; Continuous	10–25	Disintegrated structure with very poor to poor surface conditions
1–5	<25		5–10	Laminated structure with very poor surface conditions
<1	<25			

(2) For RQD > 75:

$$f_c = -7.91562RQD + 0.12152RQD^2 \quad \left(r^2 = 0.976\right) \tag{4}$$

Experimental UCS values along with aforementioned RQD have been collected from the literature. Eqs. (3) and (4) have been validated with available experimental data in the literature as shown in Fig. 3. Based on observed RQD values in the literature, UCS has been predicted and compared with the ranges given by Bieniawski (1989), as listed in Table 4. It is observed that all predicted UCS values come in the range given by Bieniawski (1989).

Fig. 4 presents the comparison between predicted UCS using Eq. (3) or (4) and experimental UCS for the observed RQD. The data in the figure are presented by different symbols to represent the predictions made for different experimental data. It is clear from the same figure that the deviations between the empirically predicted and the experimentally observed values are generally less than a factor of two and this is a considerably good agreement in view of the large variability associated with rock properties.

Variation in predicted and experimental UCSs has been attributed to the variation of rock properties, e.g. spacing and condition of discontinuities, joint spacing and number, presence of water table, etc. Hence Eq. (2) can be rewritten as follows:

(1) For RQD ≤ 75:

$$v = \frac{\left(0.59476RQD + 0.00893RQD^2\right)^{0.642} D^{-1.463}}{\gamma} \tag{5}$$

(2) For RQD > 75:

$$v = \frac{\left(-7.91562RQD + 0.12152RQD^2\right)^{0.642} D^{-1.463}}{\gamma} \tag{6}$$

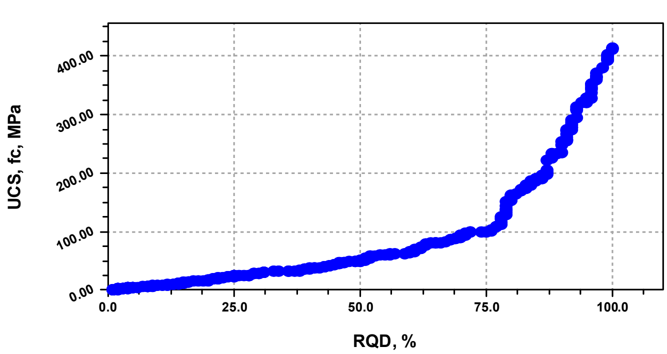

Fig. 3. Plot of 350 data points of UCS vs. RQD.

RQD for weak rock masses is zero. In such cases, GSI is very useful (Marinos et al., 2005). GSI, which was introduced by Hoek (1994), is a system of rock mass characterization used to estimate rock mass strength for different geological conditions as identified by field observations. After field visual observations of rock with respect to structure (blockiness) and surface conditions of discontinuity, GSI is evaluated from the chart given by Marinos and Hoek (2000). With the help of this chart, GSI with geological description of rock is correlated in the present study with UCS as shown in Table 3. Similar to RQD, fifty random numbers are generated for each range of GSI and the data are arranged in ascending order in each range. 300 data points were plotted, and the best fitting curve was obtained:

$$f_c = 0.3396 \times 1.02^{GSI} GSI^{1.13} \quad \left(r^2 = 0.998\right) \tag{7}$$

Experimental UCS values along with GSI have been collected from the literature. Eq. (7) has been validated with available experimental values in the literature as shown in Fig. 5. Fig. 5 presents the comparison between predicted UCS by using Eq. (7) and experimental UCS for the observed GSI from the recorded data.

Hence Eq. (2) can be rewritten as follows:

$$v = \frac{\left(0.3396 \times 1.02^{GSI} GSI^{1.13}\right)^{0.642} D^{-1.463}}{\gamma} \tag{8}$$

3. Investigation of performance of the proposed model

3.1. Prediction of PPV by present equation

The proposed curve in Fig. 1 presents the plot of experimental PPV as a function of scaled distance as obtained from Eq. (2). The scatter between the experimental data of different researchers is evident in the same figure. The goodness of Eq. (2) has been tested by estimating the correlation between the predicted and experimental values. Assuming that x = predicted PPV (the independent variable) and y = experimental PPV (the dependent variable), then

Table 4
Comparison of predicted UCS with ranges of Bieniawski (1989) from experimental RQD.

No.	RQD (%)	f_c (MPa) predicted by Eq. (3) or (4)	Range of UCS (MPa) (Bieniawski, 1989)
1	50	52	50–100
2	85	205	100–250
3	92	300	>250
4	73	91	50–100
5	60	68	50–100
6	56	61	50–100
7	40	38	25–50
8	70	85	50–100

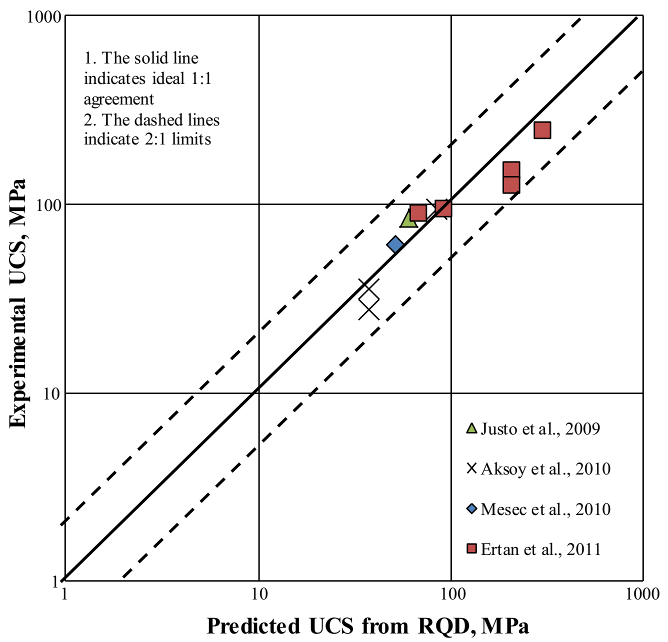

Fig. 4. Plot of experimental UCS vs. predicted UCS from RQD (Aksoy et al., 2010; Ertan et al., 2011; Justo et al., 2009).

for Eq. (2), the values of both r_{xy}^2 and s_{yx}^2 were calculated as 0.783 and 0.00018, respectively, where r is the coefficient of correlation between x and y, s is the root mean square error of estimate of y based on x. Fig. 6 presents the comparison between predicted and experimental PPVs for the available experimental data using Eq. (2). The data in the figure are presented by different symbols to represent the empirical predictions made for different experimental data. It is clear from Fig. 6 that the deviations between the

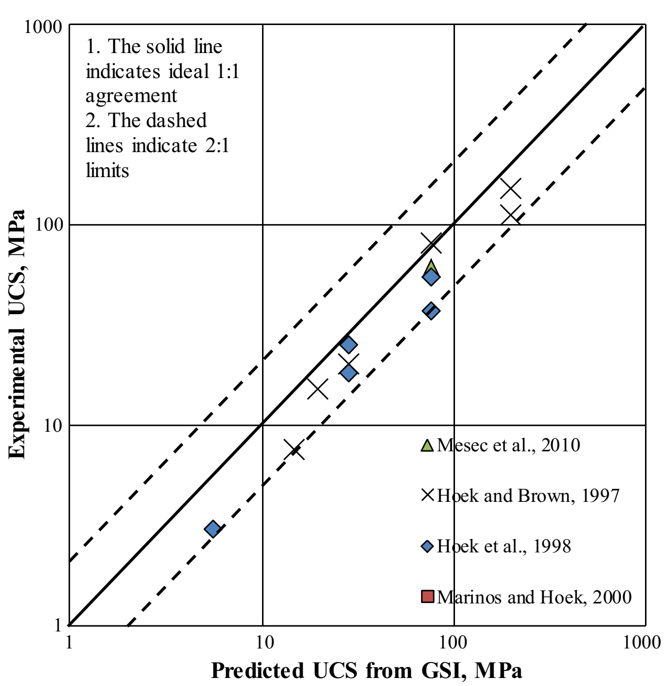

Fig. 5. Plot of experimental UCS vs. predicted UCS from GSI (Hoek and Brown, 1997).

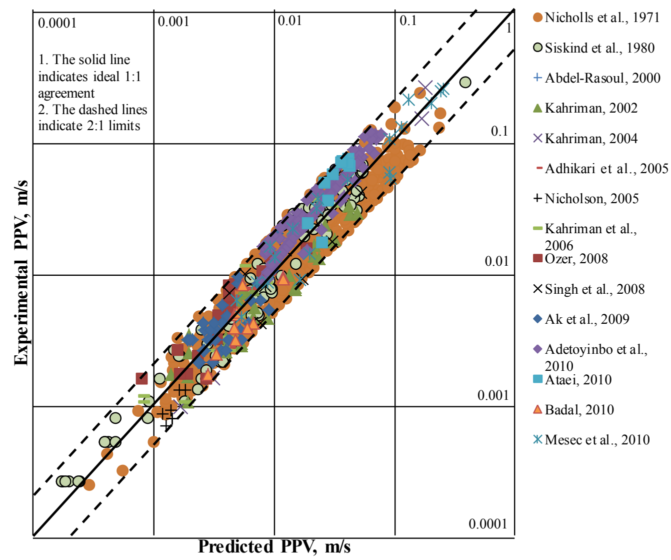

Fig. 6. Plot of PPV obtained from experiments and predictions.

empirically predicted and experimentally observed values are generally less by a factor of two and this is a considerably good agreement in view of the large variability associated with the blast phenomena.

Predictions of experimental data have been done by empirical models of Table 1. For some models, site constants are not provided in the table, e.g. USBM (Duvall and Petkof, 1959), CMRI (1993), etc. Site constants for such models are determined by plotting the experimental scaled distance vs. PPV graph. By curve fitting, site constants were determined. Table 5 illustrates the coefficient of determination and square of standard error of predictions made by methods of various researchers. It is clear from Table 5 that the current model provides better correlation between the predicted and experimental values as compared to the other existing empirical models because of the highest r_{xy}^2 and the lowest s_{yx}^2 associated with it. It is observed from Table 5 that Ozer (2008) (shale) gives the lowest r_{xy}^2 and the highest s_{yx}^2. Other models show reasonable values of r_{xy}^2 and s_{yx}^2.

Table 5
Coefficient of determination and square of standard error.

No.	Researchers	Prediction of all experimental data	
		Coefficient of determination, r_{xy}^2	Square of standard error, s_{yx}^2
1	Duvall and Petkof (1959)	0.707	0.00025
2	Nicholls et al. (1971)	0.689	0.00026
3	Siskind et al. (1980)	0.709	0.00025
4	CMRI (1993)	0.704	0.00025
5	Kahriman (2002)	0.709	0.00025
6	Kahriman (2004)	0.674	0.00028
7	Kahriman et al. (2006)	0.704	0.00025
8	Nicholson (2005)	0.699	0.00026
9	Ozer (2008) (sandstone)	0.706	0.00025
10	Ozer (2008) (shale)	0.663	0.00029
11	Ozer (2008) (limestone)	0.684	0.00027
12	Ak et al. (2009)	0.692	0.00026
13	Badal (2010)	0.709	0.00025
14	Mesec et al. (2010)	0.706	0.00025
15	Current model	0.783	0.00018

Table 6
Prediction of new experimental data of Ak and Konuk (2008).

No	Researcher	Predicted PPV (m/s)		
1	Ak and Konuk (2008) (experimental PPV)	0.0396	0.0282	0.0782
2	Duvall and Petkof (1959)	0.0520	0.0298	0.0845
3	Nicholls et al. (1971)	0.0239	0.0122	0.0429
4	Siskind et al. (1980)	0.0916	0.0532	0.1472
5	CMRI (1993)	0.0598	0.0371	0.0888
6	Kahriman (2002)	0.2901	0.1822	0.4354
7	Kahriman, 2004	0.0172	0.008	0.0327
8	Kahriman et al. (2006)	0.0515	0.0286	0.086
9	Ozer (2008) (sandstone)	0.0461	0.0302	0.0668
10	Ozer (2008) (shale)	0.2654	0.1214	0.5253
11	Ozer (2008) (limestone)	0.1803	0.0899	0.3309
12	Ak et al. (2009)	0.0964	0.0501	0.1707
13	Badal (2010)	0.0333	0.0196	0.0532
14	Mesec et al. (2010)	0.0517	0.0294	0.0846
15	Current model	0.0483	0.0264	0.0817

It is observed from Fig. 2 that present model prediction line is in between other prediction lines. Almost all prediction lines except that of Kahriman (2002) converge.

3.2. Prediction of new experimental data

Three new experimental data have been collected from Ak and Konuk (2008). The predictions by the present model and other models are presented in Table 6. It is observed from this table that the predicted PPVs by the present model are very close to the experimental values as compared to the predictions by other models.

3.3. Observation of predictions

Predictions from the equation of present study have been compared with experimental values and variation has been observed which may be owed to the reasons such as different rock conditions, different blast methods, different blast frequencies, different levels of underground water table, rock layers, different testing and measurement procedures. A further factor that would also possibly be responsible for the difference in experimentally observed and empirically predicted values is the selection of proper unit weight and UCS of rock. Therefore, considering the large variability associated with the blast phenomenon itself and also the significant difference in the reported values of PPV among the experiments of the different researchers, the proposed empirical model predicts the trends, which are in reasonably good agreement with the observed experimental trends for the PPV.

4. Conclusions

Blast-induced vibration parameters, e.g. PPV, depend upon various factors like scaled distance, vibration frequency, rock characteristics (type, unit weight, layering, slope of layers, joints, etc.), presence of water table, propagation of surface and body waves in the ground, etc. Hence, it is necessary to develop suitable empirical model for PPV. In the literature, empirical models for prediction of PPV for site-specific locations of rocks are available which cannot be generalized for use at other sites. This becomes important as complexities of rock site increase. PPV models considering effect of rock discontinuities, rock types, rock formation, rock joints and their orientation, presence of water table, soil-rock interface, etc., are also available in the literature. But effect of engineering rock properties on PPV model has not been studied yet.

(1) 1089 data (numbers) from blast experiments were obtained in terms of PPV and scaled distance for surface and near surface blasting at various rock sites are collected. Engineering rock parameters affecting blast wave propagation have been collected and assigned to the experimental data. Consequently, empirical equations are proposed for estimation of PPV considering engineering rock properties of rock, namely unit weight and UCS/RQD/GSI. Empirical equations for PPV have been developed in terms of unit weight, scaled distance and UCS.
(2) In the current study, two empirical relationships, one between RQD and UCS and another between GSI and UCS, have been established which have been validated with available experimental values taken from the literature. Current PPV model has been modified by using RQD/GSI in place of UCS.
(3) It is concluded that PPV prediction by the current model is quite reasonable up to scaled distance of 80 m/kg$^{1/2}$. It is an improvement over the existing empirical PPV models. A reduction of PPV is observed for scaled distance beyond 8 m/kg$^{1/2}$.
(4) The proposed model will be very useful for estimation of blast vibration parameters for various types of rocks considering different engineering properties. Prediction of experimental blast data from various models has been carried out. Prediction of the present model gives the maximum coefficient of determination and the minimum square of standard error.
(5) Experimental data are used to develop the present model and consequently comparison with other models has been carried out. Hence, the present model can be used by engineers in practice. In the absence of experimental data for a site, the present model will be very useful in prediction of vibration parameter due to blast in rocks. The present model will also be very useful for planning and design of blast operations. Prediction of new experimental data by the present model is closer as compared to predictions by other models. It has been found that the proposed empirical model is capable of providing the estimate of predicted PPV that reasonably matches with experimental data and published empirical predictions.

Conflict of interest

The authors wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

References

Abdel-Rasoul EI. Measurement and analysis of the effect of ground vibrations induced by blasting at the limestone quarries of the Egyptian cement company. In: ICEHM 2000. Egypt: Cairo University; 2000. p. 54–71.
Adetoyinbo AA, Popoola OI, Hammed OS, Bello AK. An assessment of quarry blasting vibration impacts in Ibadan and Abeokuta, Nigeria. European Journal of Scientific Research 2010;44(2):228–52.
Adhikari GR. Studies on flyrock at limestone quarries. Rock Mechanics and Rock Engineering 1999;32(4):291–301.
Adhikari GR, Rajan Babu A, Balachander R, Gupta RN. On the application of rock mass quality for blasting in large underground chambers. Tunneling and Underground Space Technology 1999;14(3):367–75.
Adhikari GR, Venkatesh HS, Theresraj AI, Roy Surender, Balachander R, Jain NK, Gupta RN. Role of blast design parameters on ground vibration and correlation

of vibration level to blasting damage to surface structures. Final report MT/134/02. Indian National Institute of Rock Mechanics; 2005.
Ak H, Konuk A. The effect of discontinuity frequency on ground vibrations produced from bench blasting: a case study. Soil Dynamics and Earthquake Engineering 2008;28(9):686–94.
Ak H, Iphar M, Yavuz M, Konuk A. Evaluation of ground vibration effect of blasting operations in a magnesite mine. Soil Dynamics and Earthquake Engineering 2009;29(4):669–76.
Aksoy CO, Kantarci O, Ozacar V. An example of estimating rock mass deformation around an underground opening using numerical modeling. International Journal of Rock Mechanics and Mining Sciences 2010;47(2):272–8.
Alipour A, Jafari A, Hossaini MF. Application of ANNs and MVLRA for estimation of specific charge in small tunnel. International Journal of Geomechanics 2012;12(2):189–92.
Ambraseys NR, Hendron AJ. Dynamic behavior of rock masses. In: Stagg K, Wiley J, editors. Rock mechanics in engineering practice. London: Wiley; 1968. p. 203–7.
Ashford SA, Rollins KM, Lane JD. Blast-induced liquefaction for full scale foundation testing. Journal of Geotechnical and Geoenvironmental Engineering 2004;130(8):798–806.
Ashford SA, Juirnarongrit T, Sugano T, Hamada M. Soil-pile response to blast induced lateral spreading. I: field test. Journal of Geotechnical and Geoenvironmental Engineering 2006;132(2):152–62.
Ataei M. Evaluation of blast induced ground vibrations from underground excavation at Karoun 3 area. Mining Technology 2010;119(1):7–13.
Badal KK. Blast vibration studies in surface mines. BS Thesis. Department of Mining Engineering, National Institute of Technology Rourkela; 2010.
Bell FG. Engineering geology. 2nd ed. Elsevier Ltd.; 2007.
Bieniawski ZT. Engineering rock mass classifications: a complete manual for engineers and geologists in mining, civil, and petroleum engineering. New York: Wiley-Interscience; 1989.
Bowles JE. Foundation analysis and design. 5th ed. McGraw-Hill Company; 1997.
Central Mining Research Institute (CMRI). Vibration standards. Dhanbad: CMRI; 1993.
Chakraborty AK, Pal Roy P, Jethwa JL, Gupta RN. Blast performance in small tunnels—a critical evaluation in underground metal mines. Tunneling and Underground Space Technology 1998;13(3):331–9.
Charlie WA, Veyera GE, Durnford DS, Doehring DO. Pore water pressure increases in soil and rock from underground chemical and nuclear explosions. International Journal of Engineering Geology 1996;43(4):225–36.
Daniel G. CurveExpert 1.37 (evaluation copy). 2001. http://curveexpert.webhop.biz.
Directorate General of Mines Safety (DGMS). Technical circular No. 8. Dhanbad, India: DGMS; 1982.
Duvall WI, Petkof B. Spherical propagation of explosion generated strain pulses in rock. U.S. Department of the Interior, Bureau of Mines; 1959.
Ertan M, Serhat Y, Melih I. An assessment of total RMR classification system using unified simulation model based on artificial neural networks. Neural Computing and Applications 2011;20(4):603–10.
Ghosh A, Daemen JK. A simple new blast vibration predictor. In: Proceedings of the 24th U.S. Symposium of Rock Mechanics, Texas, USA; 1983. p. 151–61.
Hao H, Wu Y, Ma G, Zhou Y. Characteristics of surface ground motions induced by blasts in jointed rock mass. Soil Dynamics and Earthquake Engineering 2001;21(2):85–8.
Hoek E. Strength of rock and rock masses. News Journal of International Society of Rock Mechanics (ISRM) 1994;2(2):4–16.
Hoek E, Brown ET. Practical estimates of rock mass strength. International Journal of Rock Mechanics and Mining Sciences 1997;34(8):1165–86.
Hoek E, Marinos P, Benissi M. Applicability of the geological strength index (GSI) classification for weak and sheared rock masses—the case of the Athens schist formation. Bulletin of Engineering Geology and the Environment 1998;57(2):151–60.
IS 6922. Criteria for safety and design of structures subject to underground blast. New Delhi, India: Bureau of Indian Standards (BIS); 1973.
ISRM. Suggested method for blast vibration monitoring. International Journal of Rock Mechanics and Mining Sciences and Geomechanical Abstract 1992;29(2):145–6.
Justo JL, Justo E, Durand P, Azanon JM. Validation of models and empirical equations to estimate deformations in jointed rock through the monitoring of a 40-storey tower foundation. International Journal of Rock Mechanics and Mining Sciences 2009;46(2):381–96.
Kahriman A. Analysis of ground vibrations caused by bench blasting at Can Open-pit Lignite Mine in Turkey. Environmental Geology 2002;41:653–61.
Kahriman A. Analysis of parameters of ground vibration produced from bench blasting at a limestone quarry. Soil Dynamics and Earthquake Engineering 2004;24(11):887–92.
Kahriman A, Ozer U, Aksoy M, Karadogan A, Tuncer G. Environmental impacts of bench blasting at Hisarcik Boron open pit mine in Turkey. Environmental Geology 2006;50(7):1015–23.
Khandelwal M, Singh TN. Prediction of blast induced ground vibrations and frequency in opencast mine: a neural network approach. Journal of Sound and Vibration 2006;289(4–5):711–25.
Khandelwal M, Singh TN. Prediction of blast-induced ground vibration using artificial neural network. International Journal of Rock Mechanics and Mining Sciences 2009;46(7):1214–22.
Kumar R, Choudhury D, Bhargava K. Response of foundations subjected to blast loadings: state of the art review. Disaster Advances 2012;5(1):54–63.
Kumar R, Choudhury D, Bhargava K. Prediction of blast-induced vibration parameters for soil sites. International Journal of Geomechanics, ASCE 2014a;14(3). http://dx.doi.org/10.1061/(ASCE)GM.1943-5622.0000355. 04014007.
Kumar R, Choudhury D, Bhargava K. Response of shallow foundation in rocks subjected to underground blast loading using FLAC3D. Disaster Advances 2014b;7(2):64–71.
Kusumi H, Matsuoka T, Ashida Y, Tatsumi S. Simulation analysis of shear behavior of rock joint by distinct element method. In: Konecny P, editor. EUROCK 2005 – impact of human activity on geological environment. London: Taylor and Francis; 2005.
Kuzu C. The importance of site-specific characters in prediction models for blast-induced ground vibrations. Soil dynamics and Earthquake Engineering 2008;28(5):405–14.
Langefors U, Kihlstrom B. The modern technique of rock blasting. New York: John Wiley and Sons; 1963.
Marinos P, Hoek EGSI. A geologically friendly tool for rock mass strength estimation. In: Proceedings of the International Conference on Geotechnical and Geological Engineering (GeoEng2000). Lancaster: Technomic Publishing Co. Ltd.; 2000. p. 1422–42.
Marinos V, Marinos P, Hoek E. The geological strength index: applications and limitations. Bulletin of Engineering Geology and the Environment 2005;64(1):55–65.
Mckay MD, Bechman RJ, Conover WJ. A comparison of three methods for selecting values of input variables in the analysis of output from a computer code. Technometrics 1979;21(2):239–45.
Mesec J, Kovač I, Soldo B. Estimation of particle velocity based on blast event measurements at different rock units. Soil Dynamics and Earthquake Engineering 2010;30(10):1004–9.
Monjezi M, Ahmadi M, Sheikhan M, Bahrami A, Salimi AR. Predicting blast- induced ground vibration using various types of neural networks. Soil Dynamics and Earthquake Engineering 2010;30(11):1233–6.
Monjezi M, Ghafurikalajahi M, Bahrami A. Prediction of blast-induced ground vibration using artificial neural networks. Tunneling and Underground Space Technology 2011;26(1):46–50.
Nateghi R. Prediction of ground vibration level induced by blasting at different rock units. International Journal of Rock Mechanics and Mining Sciences 2011;4(6):899–908.
Nicholls HR, Charles FJ, Duvall WI. Blasting vibrations and their effects on structures. U.S. Department of the Interior, Bureau of Mines; 1971.
Nicholson RF. Determination of blast vibrations using peak particle velocity at Bengal Quarry, in St Ann, Jamaica. MS Thesis. Lulea, Sweden: Department of Civil and Environmental Engineering, Division of Rock Engineering, Lulea University of Technology; 2005.
Ozer U. Environmental impacts of ground vibration induced by blasting at different rock units on the Kadikoy–Kartal metro tunnel. Engineering Geology 2008;100(1–2):82–90.
Pal Roy P. Vibration control in an opencast mine based on improved blast vibration predictors. Mining Science and Technology 1991;12(2):157–65.
Pal Roy P. Putting ground vibration predictors into practice. Colliery Guardian 1993;241(2):63–7.
Pal Roy P. Characteristics of ground vibrations and structural response to surface and underground blasting. Geotechnical and Geological Engineering 1998;16(2):151–66.
Rai R, Singh TN. A new predictor for ground vibration prediction and its comparison with other predictors. Indian Journal of Engineering and Material Sciences 2004;11:178–84.
Rai R, Shrivastva BK, Singh TN. Prediction of maximum safe charge per delay in surface mining. Transactions of the Institution of Mining and Metallurgy, Section A: Mining Technology 2005;114(4):227–31.
Singh TN, Dontha LK, Bhardwaj V. Study into blast vibration and frequency using ANFIS and MVRA. Transactions of the Institution of Mining and Metallurgy, Section A: Mining Technology 2008;117(3):116–21.
Siskind DE, Stagg MS, Kopp JW, Dowding CH. Structure response and damage produced by ground vibration from surface mine blasting. U.S. Department of the Interior, Bureau of Mines; 1980.
Unified Facilities Criteria (UFC) 3-340-02. Structures to resist the effects of accidental explosions. U.S. Department of Defense; 2008.
Wu YK, Hao H, Zhou YX, Chong K. Propagation characteristics of blast induced shock waves in a jointed rock mass. Soil Dynamics and Earthquake Engineering 1998;17(6):407–12.
Wu C, Lu Y, Hao H, Lim WK, Zhou Y, Seah CC. Characterization of underground blast induced ground motions from large scale field tests. Shock Waves 2003;13(3):237–52.

Web references

Rocscience Inc. Rock mass properties. http://www.rocscience.com/documents/hoek/corner/12_Rock_mass_properties.pdf, [last accessed on 31.07.12].
Densities of Common Rock Types, http://www.geology.about.com/cs/rock_types/a/aarockspecgrav.htm_properties.pdf, [last accessed on 31.07.12].
Mechanical Properties of Dolomitic Limestone, http://www.ehow.com/list_6902102_mechanical-properties-dolomitic-limestone.html, [last accessed on 31.07.12].
Pillar Design and Coal Strength, http://www.cdc.gov/niosh/pdfs/97-133-c.pdf, [last accessed on 31.07.12].
Density of materials, http://www.simetric.co.uk/si_materials.htm, [last accessed on 31.07.12].

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