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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 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).

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)	$v = k(R/Q^{1/2})^{-b}\mathrm{e}^{-\alpha R}$
8	Ghosh and Daemen (1983)	$v = k(R/Q^{1/3})^{-b}\mathrm{e}^{-\alpha R}$
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)	$v = kR^{-b}Q_{\mathrm{max}}\mathrm{e}^{-\alpha}$
16	Nicholson (2005)	$v = 0.438D^{-1.52}$
17	Rai et al. (2005)	$Q_{\mathrm{max}} = k(vD^2)^b$
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)	$v = 0.508D^{-1.37}$

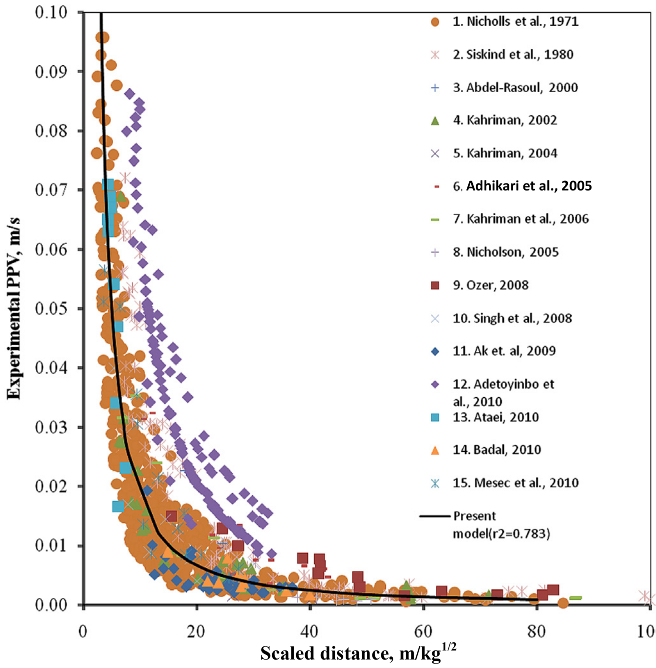

Fig. 1. Experimental PPV as a function of scaled distance.

It is clear from the above analyses that effects of various rock characteristics on PPV model have been studied by various